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Section Ecosystem Data Analysis and Modelling
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and
Management Unit of the North Sea Mathematical Models (MUMM)

The impact of sand extraction on the wave height near the Belgian coast

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I. Introduction

Over the last years, the extraction of marine aggregates is increasing considerable. While in the period 2003-2010, the total volume of extracted marine aggregates on the Belgian Continental Shelf stayed below 2.5 Mm^3, since 2011 the extraction increased, with peaks at 2013, with an extraction of more than 4.0 Mm^3, and 2014, with an extraction of even more than 6.0 Mm^3 (Van den Branden et al., 2016). Furthermore, since 2012, concessions were granted in the region of the offshore Hinderbanks. The volumes are mostly needed in response to the needs of the Coastal Safety Plan bringing the level of protection against extreme storm events at a 1:1000 years return period (www.kustveiligheid. be).

The limits of the extraction in the Belgian Law is set at 5 m below the reference level, that was defined by the Service Continental Shelf of the Federal Public Service Economy (COPCO) (Law of 13 June 1969 on the exploration and the exploitation of non-living resources of the territorial sea and the continental shelf, changed by the law of January 20th, 1999 and April 22th, 1999). This reference model is based on a detailed terrain model of the sea bottom in the extraction zones, measured during multi-beam surveys in the first half of the previous decennium. Based on this limit, three areas in the extraction Sector 2 (KBMA, KBMB and BRMC), where extraction led to a deepening of more than 5 m, were closed (see Figure 1). In other areas in Sector 1 (TBMAB) and Sector 4 (HBMC), this limit is approached as well, which will lead to the closure of these areas, based on the current legislation.

This method however doesn't take the structure of the sea bottom and the differences in impact into account. Furthermore, the sustainable character of the marine aggregate extraction becomes at risk. The areas with the best quality sands (median size to coarse sands) are being closed while zones with economically less interesting quality (fine sands) remain open. Therefore, COPCO started with a new project to define a new extraction limit levels, which were based on scientific and economic criteria (Degrendele, 2016; Degrendele et al., 2017). The goal of these new extraction limit levels is to limit the impact of the extraction in the most sensitive areas for sediment and habitat and to increase the economic sustainability, by accounting for the available volumes and the quality of the sands. Three scenarios were proposed: a maximum, minimum and medium scenario. Remark that in the new scenarios, the total volume of the reserves, i.e., the total volume that could be extracted, decreases from about 1050 Mm^3 to 927 Mm^3, 538 Mm^3 or 599 Mm^3 respectively. At the moment, the scenario 3 is the preferred one.

In Van den Eynde (2016; 2017), the effect of these new proposed extraction limit levels on the changes in the bottom stress were evaluated, according to the Belgian implementation of the European Marine Strategy Framework Directive (Belgian State, 2012; 2018). In this Directive, it was stated that human impacts need consideration when the bottom shear stress, calculated with a validated numerical model, changes with more than 10 % at a specified distance of the activity. The impact of extraction of marine aggregates, up to the new proposed extraction limit levels, was evaluated with this respect. Simulations were executed with numerical models to test whether the three newly proposed extraction limit levels were within these constraints.

Results showed that for the medium scenario 3, no problems occurred for most sectors and that only for an area of 4.90 km² remained, west of Sector 2c, the bottom stress changes with more than 10 % outside the buffer zone. A solution was proposed to increase the extraction limit level to such a level, that no bottom stress changes higher than 10 % are still present, outside the buffer zone.

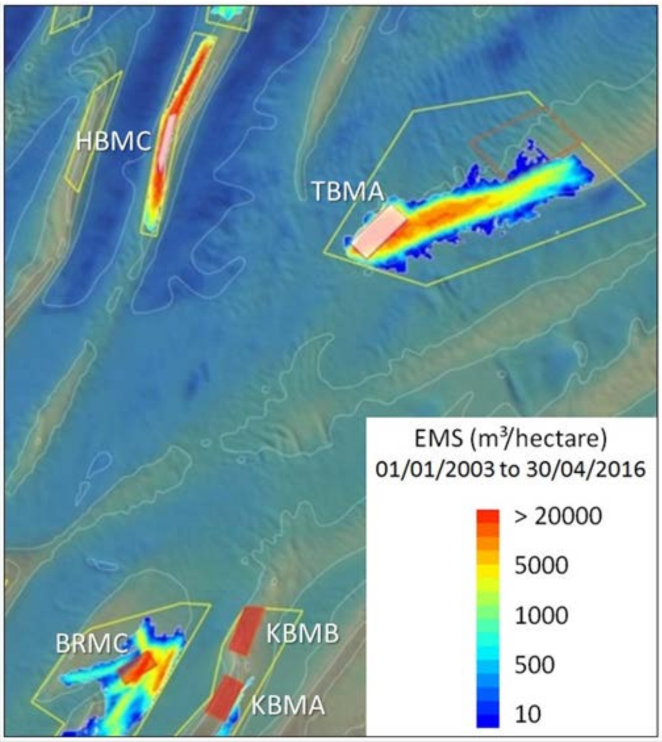

Figure 1: Areas, closed for extraction (red) and areas where the limit is almost reached (rose) (from: Degrendele, 2016).

In this report, the effect of the change of the extraction level limit on the wave propagation on the Belgian continental shelf is investigated. This is done using the SWAN wave model. From these results the effect of the extraction on coastal protection is evaluated.

Remark however that in the current report the Sector 4a is not considered anymore and a new extraction Sector 5 is being defined. The simulations are executed for these extraction sectors. Remark also that in the current report Sector 3 (Sierra Ventana) is out of scope.

In the first section the model is shortly presented. The second section discusses the setup op the model grid. In the third section, the simulations are presented, while a discussion is presented in the next section. A conclusion in formulated in the last section.

2. Numerical model

For the propagation of the waves over the shallow Belgian coastal waters, different models can be used. For the operational forecasts of the waves on the Belgian coast, the third generation WAM model is used (WAMDI Group, 1988; Günther et al., 1992). The local grid however only a resolution of 0.033° in latitude and 0.022° in longitude, which is more than 1.5 km.

Therefore, for this study the SWAN model (e.g., Ris, 1997; Booij et al., 1999; Holthuijsen et al., 1989, 1993, 2003) is used. The SWAN model is a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters. The model calculates in time and space, the generation of waves, their propagation and shoaling, non-linear wave-wave interaction, white-capping, bottom friction and depth-induced breaking. In comparison with the WAM model, the model is more suited to calculate the propagation of the waves in the nearshore area. The main disadvantage is that the models is preferably used in stationary mode. The SWAN model is implemented (see next session) on a grid of 250 m x 250 m, better representing the sand banks. This is needed to evaluate the effect of sand extraction on the wave propagation.

In the current project, the SWAN cycle III version 40.51 is used (SWAN, 2006a, 2006b).

3. Development of the bathymetries

3.1. New SWAN bathymetry

In the framework of the CLIMAR project (Van den Eynde, 2011; Van den Eynde et al., 2011), the SWAN model was used to simulate the propagation of the waves from offshore to the Belgian coast and to investigate the effect of sea level rise on the wave propagation. For that application, the model was implemented on a Cartesian grid, rotated over 25.5° anti-clockwise, along the Belgian coast, with a resolution of 250 m x 250 m, a grid that was prepared by KULeuven & FHR (2004). The rotation is needed to assure that the distance from the coast to the offshore boundaries are similar. This assures that the time of the waves, travelling from the offshore conditions to the shore takes the same time, which is useful, using the model in stationary mode. The lower left point of the grid had the co-ordinates (50°54'00", 2°07'12"). This grid was 125 km long (along the coast) and 39 km wide (offshore). The model bathymetry is shown in Figure 2.

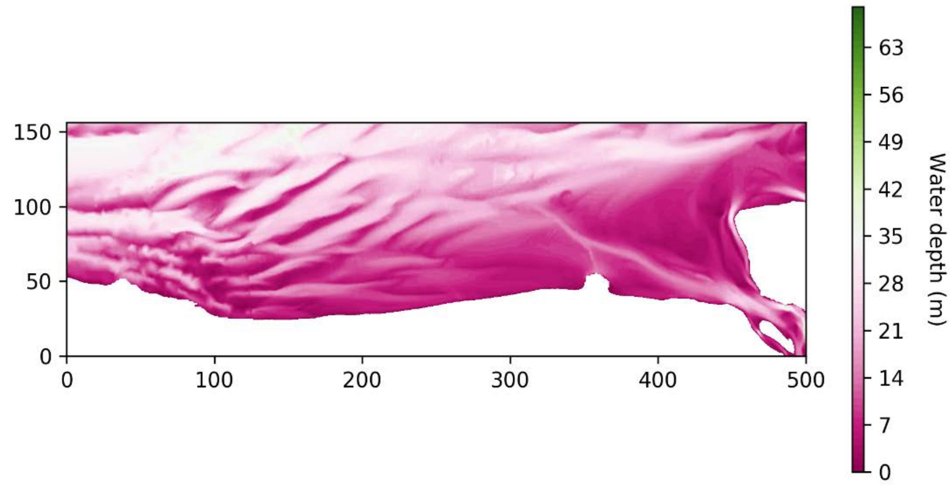

Figure 2: Bathymetry and extension of the SWAN model grid, used in the CLIMAR project (Van den Eynde et al., 2011).

Unfortunately, this model grid is not extended enough to the north (offshore) to include the extraction sectors in the Hinderbank area. Therefore, it was decided to construct a new bathymetry in the framework of this project that uses the same characteristics but is extended more offshore.

The new model grid is based on the new bathymetries that were developed for the new hydrodynamic model train, based on the COHERENS software, that is being installed at the RBINS-OD Nature (Dulière, 2017). The BeC grid has a resolution of 250 m x 250 m and covers the entire Belgian Continental Shelf. Since the SWAN model is rotated, not all points in the new SWAN grid are covered by the BeC grid. In the northwest corner, data from the SoB grid were used, which has a resolution of 750 m x 750 m, and covers the Southwestern part of the North Sea (Dulière, 2017). More than 90% of the new grid points were interpolated from the BeC grid, while less than 10% is interpolated from the SoB grid.

Some differences between the new grid and the old grid can be found. Since for the old grid, the TAW reference was used, while for the new grid, Mean Sea Level was used as reference (for the hydrodynamic models), an overall difference between the two bathymetries was expected. When comparing the points that are sea points in both grids, a difference of 2.61 m was calculated. This is some 0.28 m higher than the expected difference between TAW and MSL for Ostend (Vlaamse Hydrografie, 2011).

Furthermore, the coastline of the two models do not perfectly match. In 120 points, points were land in the original grid, while they are sea in the new grid. This is mainly around or in the harbours of Dunkerque or Zeebrugge, or in the Westerschelde. On the other hand, 1437 land points in the new grid, were sea points in the old grid. These are mainly grid points near the coast, with very low or negative bathymetries in the old grid, where in the grid from Dulière (2017), the grid points were put to land, to avoid stability problem in the hydrodynamical model. These grid points were put to sea in the new grid, taking into account the difference between the reference level of the old and the new grid.

In Figure 3, the new bathymetry is shown, while in Figure 4 the differences between the old and the new bathymetry is shown, corrected for the overall difference of 2.61 m.

Large differences can be seen in the western part of the grid, at the French Continental Shelf. Although there is no reason to expect that the grid from Dulière (2017) has less quality in that part of the grid, the results are however striking. De Maerschalck (FHR, pers. comm.) pointed out that that part of the grid is not well represented in the new bathymetry. Therefore, in that part of the grid, the old bathymetry was kept.

The final bathymetry is shown in Figure 5. In the figure, also 10 possible output points before the Belgian coast are show where the output could be used by coastal models such as the XBeach model (Roelvink et al., 2009; 2015) and the UNIBEST-CL+ model (https://www.deltares.nl/en/software/unibest-cl/). The XBeach model is operated by Flanders Hydraulics Research (FHR) to evaluate the changes of the beach profiles during storms (De Roo et al., 2015; Kolokythas et al., 2016). The UNIBEST-CL+ model is operated to simulate larger scale coastline dynamics. These points were taken from IMDC (2009) to represent the wave climate for the 10 coastal municipalities. The information on these 10 points is given in Table 1.

For the Belgian coast, 260 section are defined (De Roo et al., 2014) that could be used for output and for evaluation of the beach profiles. The points are normally defined at the -5 TAW level, or at a distance of 1500 m out of the coast. Output at all these section points could be provided if necessary.

Table 1: Output points at the coastal municipalities and at Westhinder. Depth is model depth.

Output point	Abbreviation	Easting (m)	Northing (m)	Depth (m MSL)
De Panne	Dpa	470931	5662065	7.4
Koksijde-Oostduinkerke	Kok	473498	5664586	5.3
Nieuwpoort	Nwp	479850	5667537	7.6
Middelkerke-Westende	Mid	486455	5671160	6.9
Oostende	Oos	492895	5675867	7.7
Bredene	Brd	495981	5679099	7.0
De Haan-Wenduine	DHn	501611	5681711	7.3
Blankenberge	Bla	508487	5686226	7.5
Zeebrugge	Zbr	511637	5691881	16.4
Knokke-Heist	Knk	519616	5689721	8.1
Westhinder	Whi	461338	5692842	25.8

In Figure 6 and Figure 7, the differences between the old and the new bathymetry are shown. Since in the French part of the bathymetry, the old bathymetry was kept, no differences are found in that part of the grid. Figure 7 zooms in on the differences between -4 m and +4 m. Larger differences can be found in the North of the area, near the fair channels and in the Westerschelde. Since no output points are defined in the Westerschelde, the larger differences in the new grid are not important in this case.

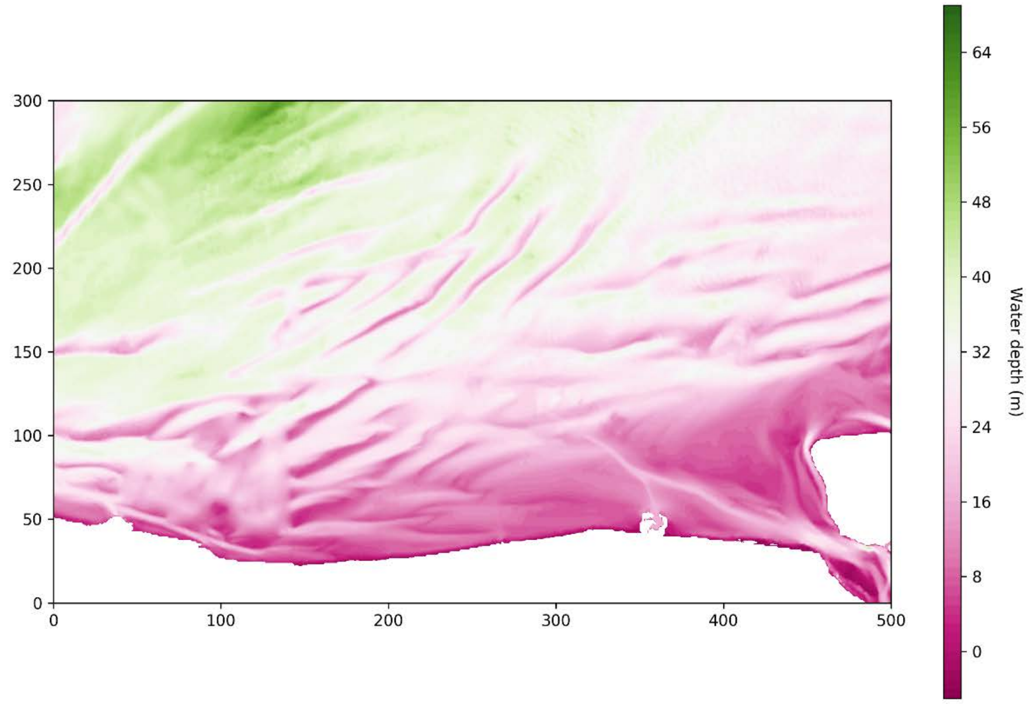

Figure 3: New extended SWAN grid, based on the old SWAN grid and the BeC and SoB hydrodynamical grids. Reference levels is MSL.

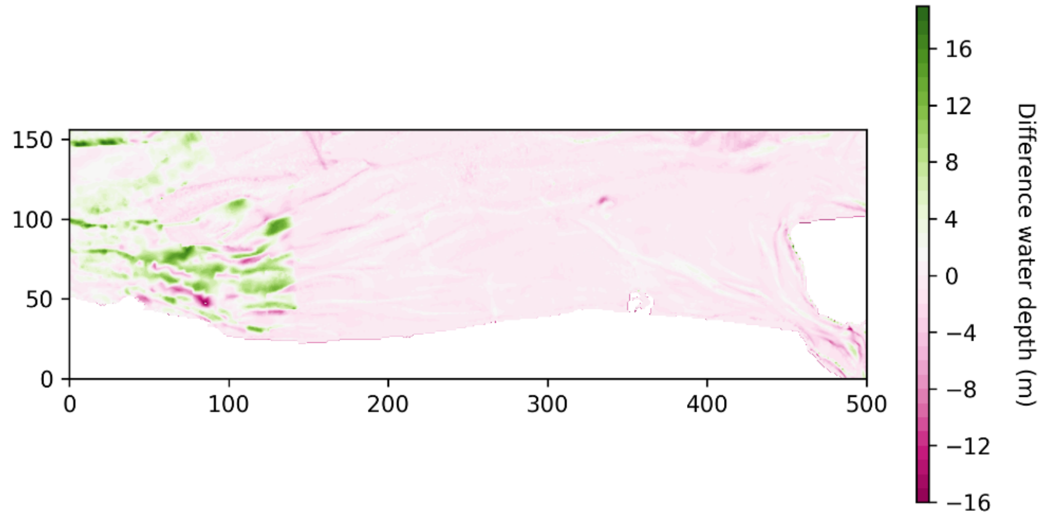

Figure 4: Differences between old and new extended SWAN grid.

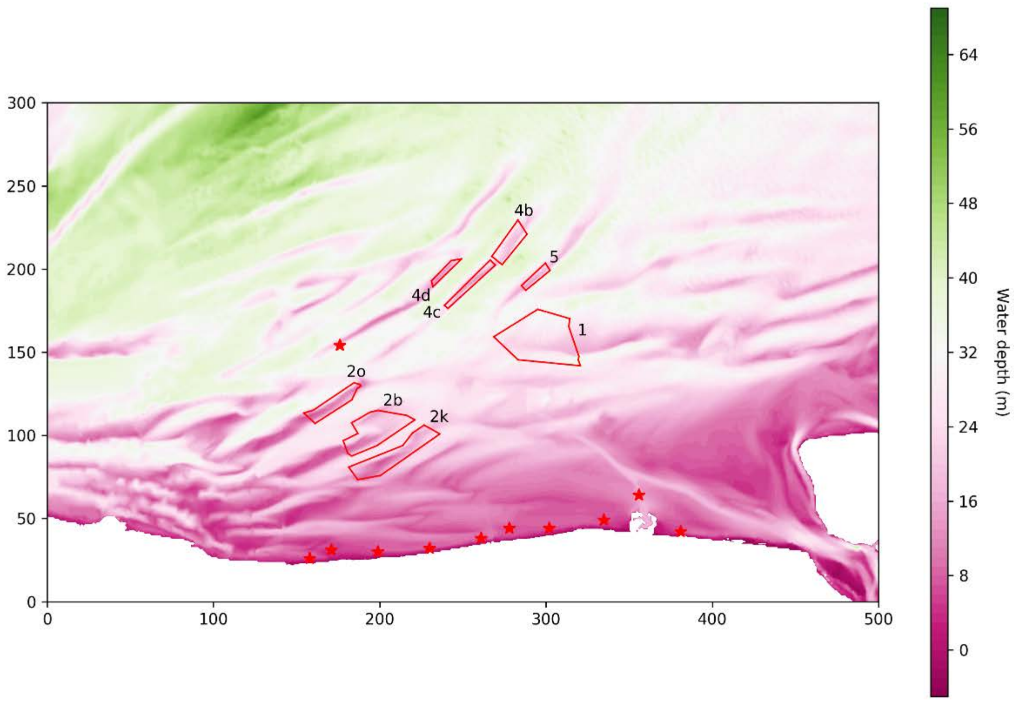

Figure 5: New extended SWAN grid, based on the old SWAN grid and the BeC and SoB hydrodynamical grids. Reference levels is MSL. Points are output points at the coastal municipalities and the wave buoy at Westhinder (offshore). The extraction zones are indicated.

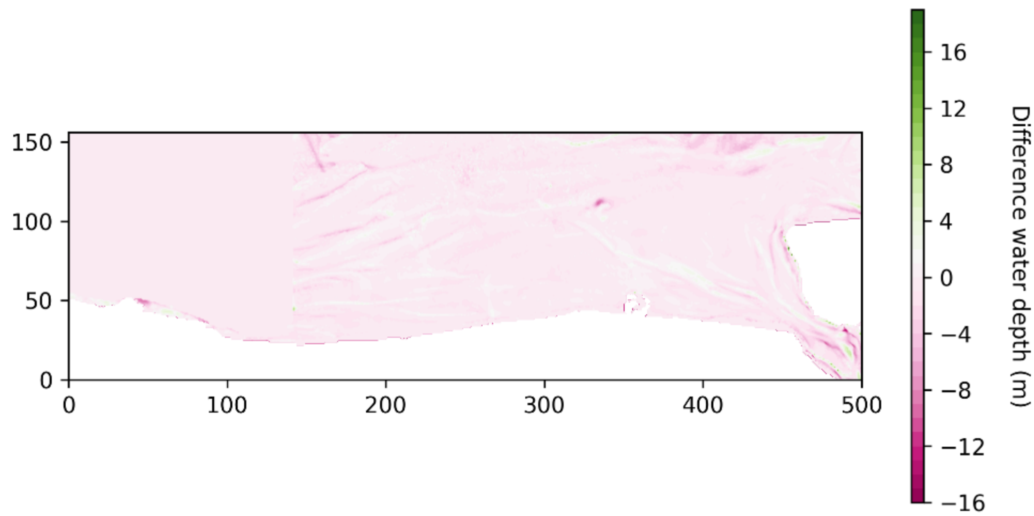

Figure 6: Differences between old and new extended SWAN grid, with original French part.

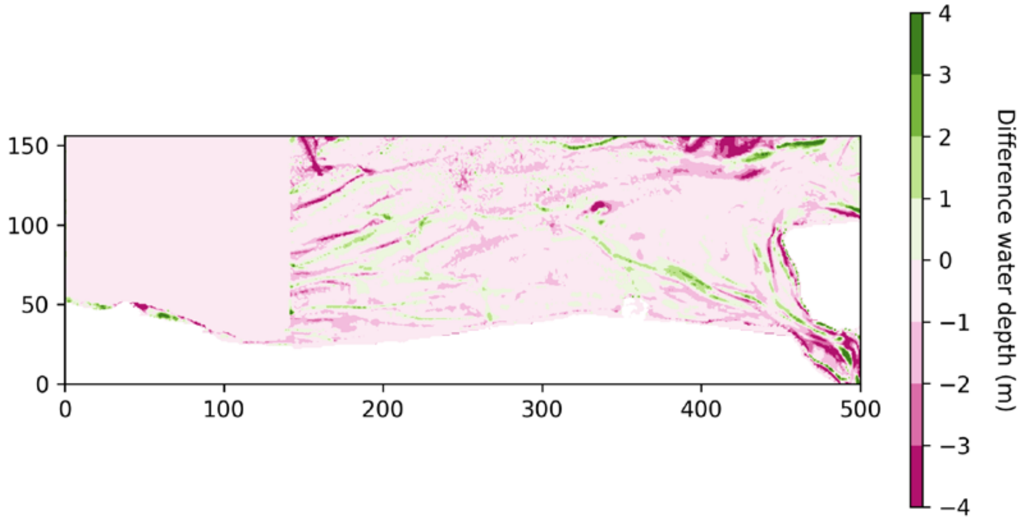

Figure 7: Differences between old and new extended SWAN grid, with original French part, zoomed in between -4 m and +4 m.

3.2. *Inclusion of the new reference level at the extraction Sectors*

To check the influence of the sand and gravel extraction, the bathymetry of the SWAN grid is adapted in the extraction zones to the newly proposed extraction levels. The position of the extraction sectors in the SWAN grid is shown in Figure 8.

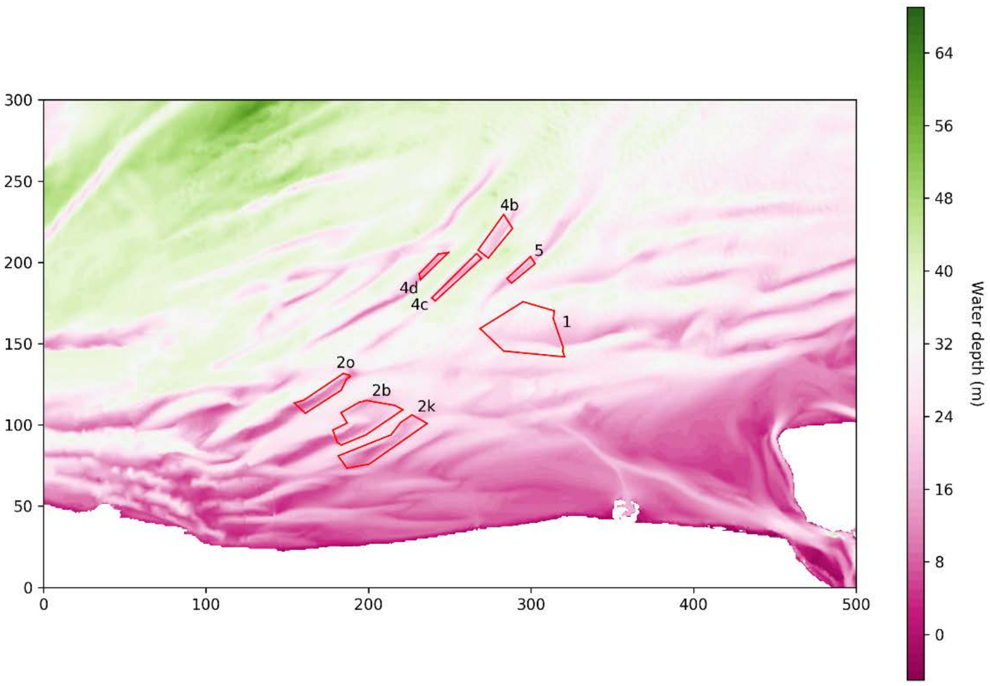

Figure 8: Position of the different extraction sectors in the SWAN grid.

For the present bathymetry and for the newly proposed extraction limit level, bathymetrical files were received on a grid of 5 m x 5 m for the different sectors from COPCO. To make the inclusion of these data consistent, both data sets were included in the SWAN bathymetry. A similar procedure is used, as was used in Van den Eynde (2016; 2017).

First, a new reference bathymetry was prepared based on the COPCO data. By averaging, the bathymetry for the grid cells of the model grid were derived. An average was only taken when at least 500 points could be used.

It can be noted that the differences between the reference bathymetry provided by COPCO and the bathymetry of the new SWAN grid vary between +0.17 m and -0.75 m, with the COPCO reference bathymetry being deeper for all sectors, except for sector 4c. These values are similar than the differences that were observed in Van den Eynde (2017). The fact that the COPCO reference bathymetry is less deep in the sector 4c than the SWAN grid is however surprising and is caused by the differences in the hydrodynamic grids that were used to construct the SWAN grid (Dulière, 2017). To make the introduction of the COPCO data in the SWAN bathymetry more consistent, the COPCO bathymetries were shifted over the difference for the different zones.

Since tests in Van den Eynde (2017) showed that adapting the borders to ensure a more smooth transition between the grids didn't improve the results, this was not done in this report.

In Figure 9, the difference between the (shifted) reference COPCO bathymetry and the bathymetry of SWAN is shown, for the sector 1. Some differences between the bathymetries are clear. Mainly at the southwestern part of the zone, some larger differences are visible.

Table 2: Difference between depth in the COPCO reference bathymetry and the SWAN bathymetry for the different sectors.

Sector	Difference (m)
1	-0.74
2b	-0.26
2k	-0.75
2o	-0.60
4b	-0.63
4c	0.17
4d	-0.29
5	-0.57

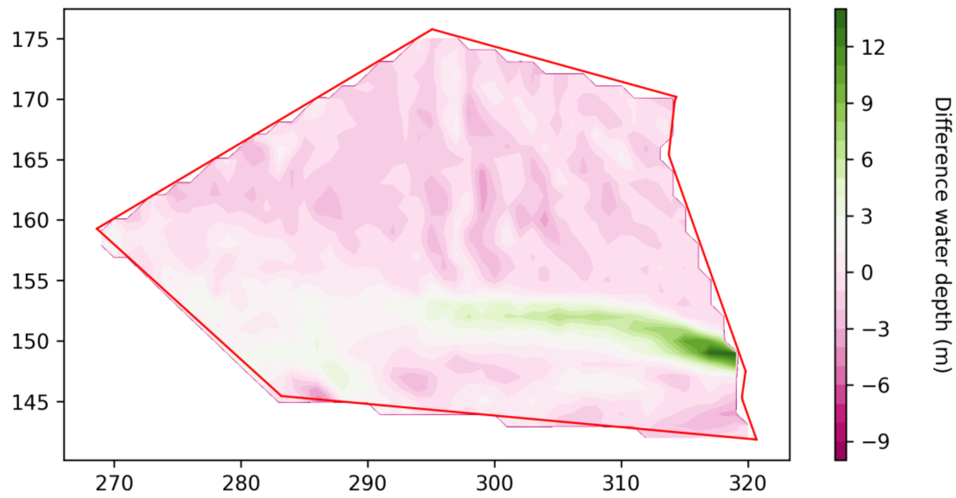

Figure 9: Difference between the (shifted) COPCO reference bathymetry and the SWAN bathymetry for the sector 1.

In Figure 10, the final bathymetry with the included COPCO bathymetry is shown for the sector 1.

After the preparation of the new reference bathymetry, the same procedure was followed to prepare the new bathymetry, where the bathymetry in the extraction zones was lowered to the new (proposed) extraction limit. The bathymetries were again first averaged over the model grid cells and were shifted over the same difference, that was found between the reference bathymetry and the SWAN model bathymetry. The bathymetry for the new extraction limit for sector 1 is shown as an example in Figure 11. In Figure 12, the difference between the reference bathymetry and the extraction limit bathymetry is shown for the same zone. In Figure 13, the difference between the reference bathymetry is shown for a cross-section of the bathymetry at Y=195, where the sectors 4c, 4d and 5 are cut.

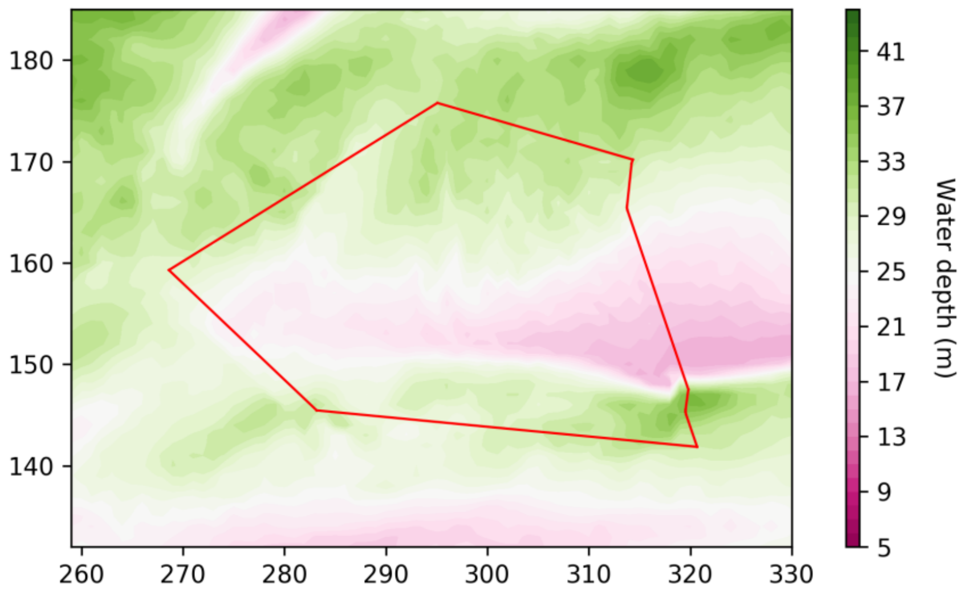

Figure 10: New bathymetry for the sector 1, based on the COPCO bathymetry.

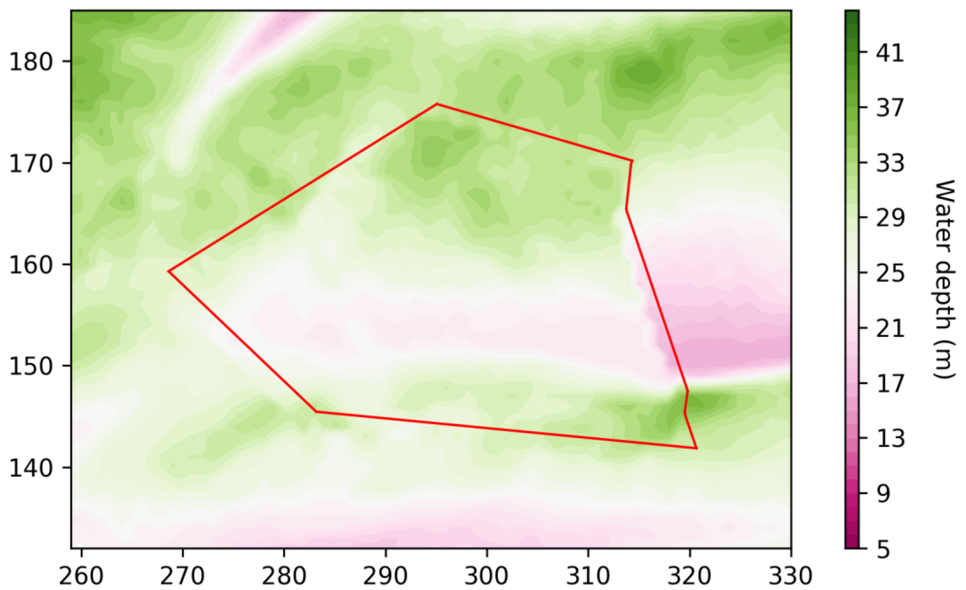

Figure 11: New extraction limit bathymetry for the sector 1, based on the COPCO bathymetry.

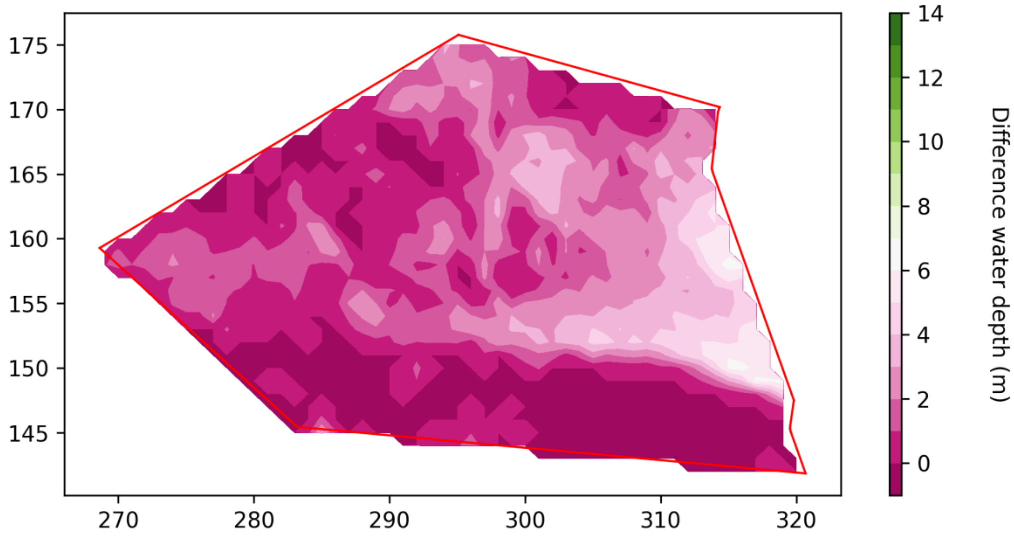

Figure 12: Difference between the reference bathymetry and the extraction limit bathymetry for the sector 1.

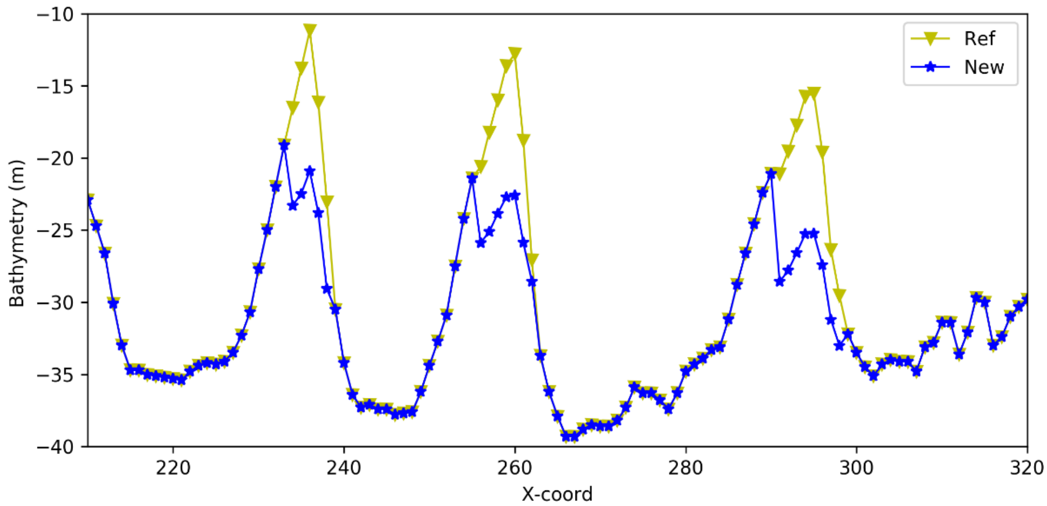

Figure 13: Difference between the reference bathymetry and the extraction limit bathymetry at Y=195.

Some information on the area of the different sectors for the different sectors can be found in Table 3. Sector 1 is clearly the largest zone, with a size of 73 km², while sector 4d and the new sector 5 are the smallest ones, with a size of only 5.2 km² and 6.2 km² respectively. In the Table 3, also the volume is given of the marine aggregates that could be extracted. The largest amount can be extracted in sector 1, namely about 93 Mm³. In the other sectors, the extractable amount varies between 35.7 Mm³ (sector 4d) and 85.4 Mm³ (sector 2b). Remark that in the sector 1 only 1.28 m can be extracted on average over the entire sector, while in sector 5, more than 7 m can be extracted on average over the zone. In total a volume of 508 Mm³ can be extracted in the different sectors.

Table 3: Area and the volume extracted for the different extraction sectors.

Sector	Area (km^2)	Extraction (Mm^3)	Extraction/Area (m)
1	73.1	93.23	1.28
2b	39.4	85.37	2.16
2k	34.7	66.03	1.90
2o	17.2	52.10	3.03
4b	14.9	63.98	4.30
4c	10.5	66.53	6.34
4d	5.2	35.68	6.80
5	6.2	44.94	7.26
TOT	201.2	507.86	2.52

4. Modelling the effect of extraction on wave propagation

4.1. *Introduction*

In a first section, some small tests with the boundary conditions will be presented and some parameters in the SWAN model will be explained. In the main part, simulations with the reference and the extraction limit bathymetry will be presented for different wave heights and wave directions. Simulations of the 1000 yearly storm for the Belgian coast, including possible sea level rise will be discussed in the next section.

4.2. *SWAN model and boundary conditions*

4.2.1. General information

The SWAN model, version 40.51, is used with most of the default values. The model grid was already discussed in the previous sections. The wave spectra in the model are described for 37 frequencies within the frequency range of 0.025 Hz to 0.85 Hz. The frequencies are logarithmic distributed. The full directional range is covered with a resolution of 10°.

The model uses the 3th generation source files, including linear and exponential wind growth, white capping, non-linear 4-wave interactions (so-called quadruplets), depth-induced wave breaking, bottom friction and non-linear shallow water 3-wave interactions (so-called triads). The triads and bottom friction, non-active by default, were activated.

The model was run in stationary mode, with default accuracy parameters and with maximum 40 iterations. Normally around 7 iterations are used in the current calculations.

While recent research by Zijlema et al. (2012) showed that in older versions of SWAN (like the 40.51 version) wave growth by wind was overestimated, which was compensated by larger bottom friction for wind sea, the lower bottom friction was not included here, because the new wave growth formulations were not included in the 40.51 version of the model

Simulations were only executed for winds to the shore, covering the wind directions from South-West (SW) over North (N) to North-East (NE) with a resolution of 22.5°. Remark that the winds from NNW is almost a wind perpendicular to the shore. At the boundaries a Jonswap spectrum is applied with a peak enhancement parameters γ of 3.3, representing a (fully developed) wind sea spectrum. The directional width is set to 30°, in agreement with the results of the tests by IMDC (2009). The waves are characterised by a significant wave height *Hs*, a peak period *Tp* and a wave direction *Dir*. A constant wind was applied with a wind speed *Ws*. The wave direction at the boundary was assumed to be the same as the wind direction.

4.2.2. Boundary conditions

In IMDC (2009) some tests have been executed to check the influence of applying boundaries at the northern boundary alone or at the northern and western boundary of the model grid. It was stated that applying waves at the eastern boundary was not important, due to the limited effect of these boundaries at the Belgian coast, as they used the model grid, set up by KULeuven and FHR (2004), which was limited offshore to Westhinder. The results showed that for the Belgian coast, the effect of the boundaries was not too important. Since the model grid has been extended considerable to the North in this project, some initial test to check the influence of the boundary conditions on the results at the Belgian coastal stations were carried out.

To check the influence of the boundary conditions, six simulations were executed: three simulations with waves applied at the northern, western and eastern boundary, and three simulations with waves, only applied at the northern boundary. The waves at the boundaries had a significant wave height of 2 m and a peak frequency of 7 s. The water level was set at 0 m TAW, i.e. at -2.33 m below MSL. Wind speed was set at 14 m/s, with wind and wave directions from SW, NNW and NW. In Figure 14 and Figure 15, the significant wave height is shown with respectively boundaries at the N, E and W and with boundaries from the N only and for waves and wind from the NNW (perpendicular to the coast). The difference between the two maps is shown in Figure 16.

The difference in the points near the coast are shown in Figure 17. The Belgian zone is shaded. One can see that the differences in this case are mainly at the western and eastern boundaries and that the difference at the Belgian coast is limited.

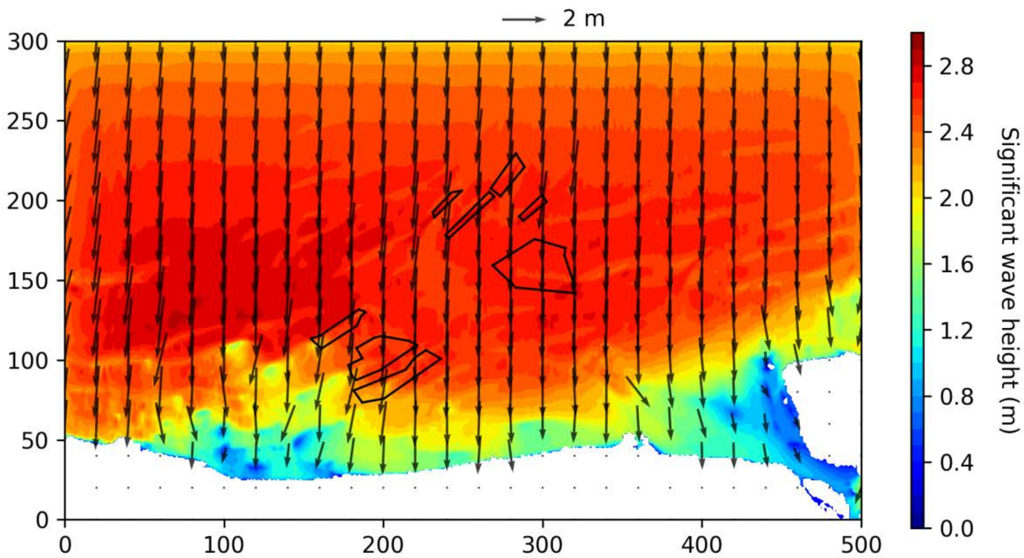

Figure 14: Significant wave height with boundaries at N, E and W. Waves at boundaries: Hs=2.0m, Tp=7s, Dir=NNW; wind speed Ws=14 m/s.

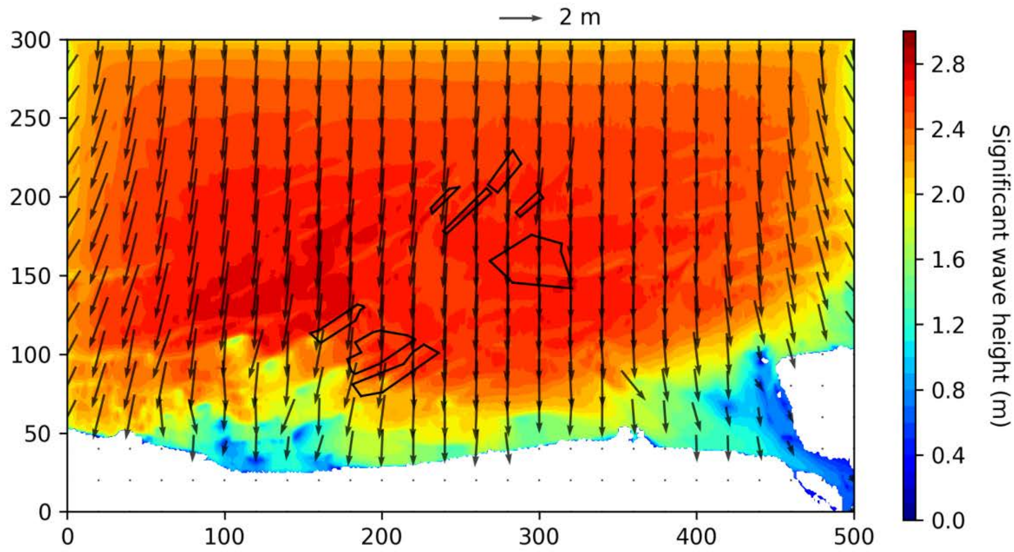

Figure 15: Significant wave height with boundaries at N. Waves at boundaries: Hs=2.0m, Tp=7s, Dir=NNW; wind speed Ws=14 m/s.

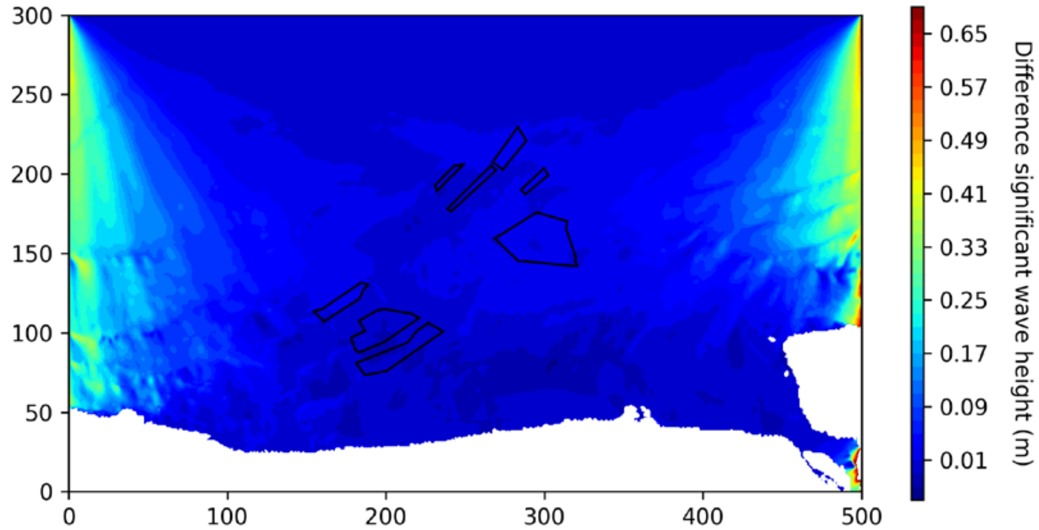

Figure 16: Difference in significant wave height between simulation with boundaries at N, E and W and simulation with boundaries at N. Waves at boundaries: Hs=2.0m, Tp=7s, Dir=NNW; wind speed Ws=14 m/s.

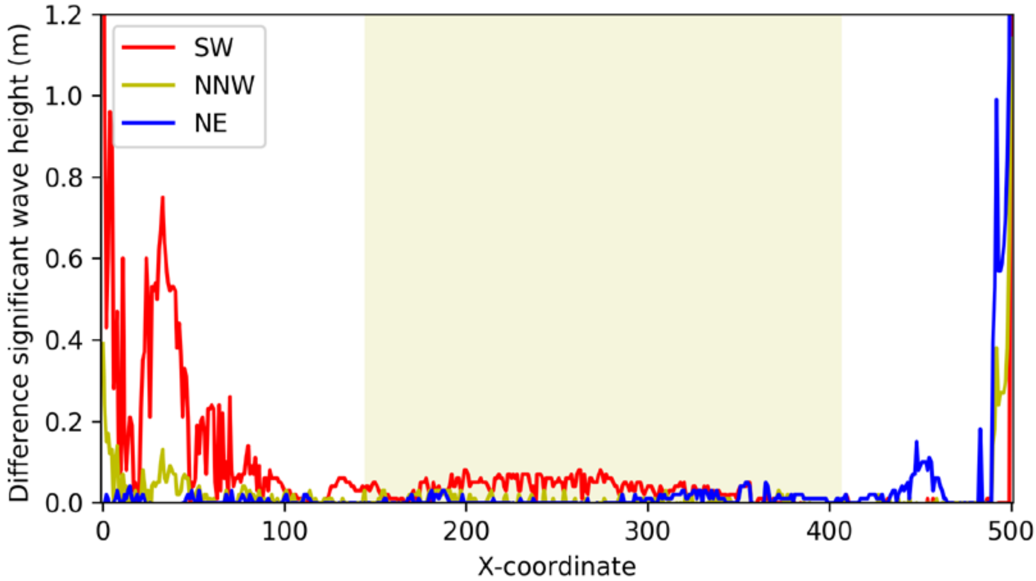

Figure 17: Difference in significant wave height between simulation with boundaries at N, E and W and simulation with boundaries at N at the points near the coast. Waves at boundaries: Hs=2.0m, Tp=7s, wind speed Ws=14 m/s. Different wind directions. Belgian zone is shaded.

The same differences maps are shown for waves and winds coming from the SW and NE respectively in Figure 18 and Figure 19. One can see that for these other wave and wind directions, the differences at the border itself are much larger, but that the influence at the Belgian coasts itself remains limited. This can also be seen again in Figure 17.

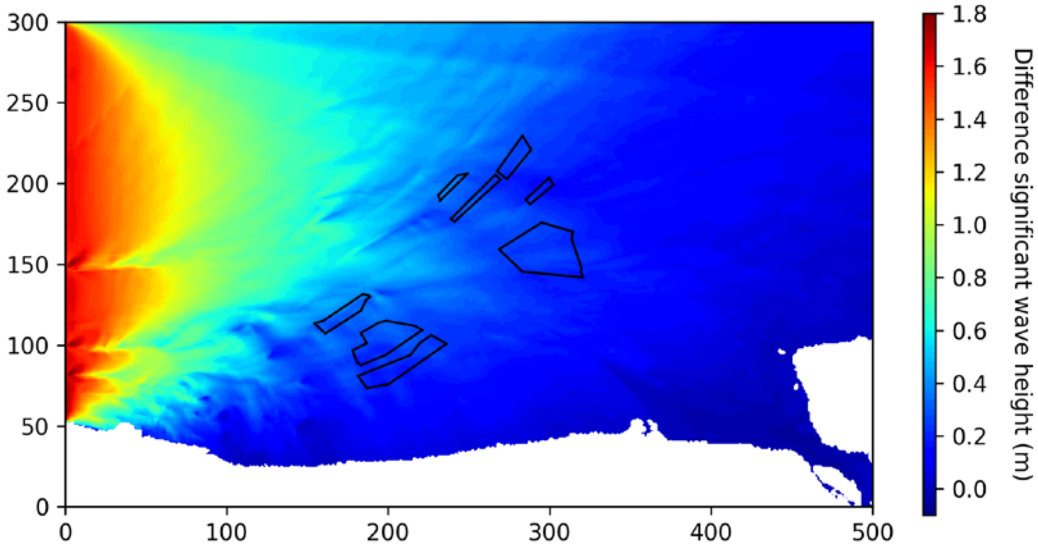

Figure 18: Difference in significant wave height between simulation with boundaries at N, E and W and simulation with boundaries at N. Waves at boundaries: Hs=2.0m, Tp=7s, Dir=SW; wind speed Ws=14 m/s.

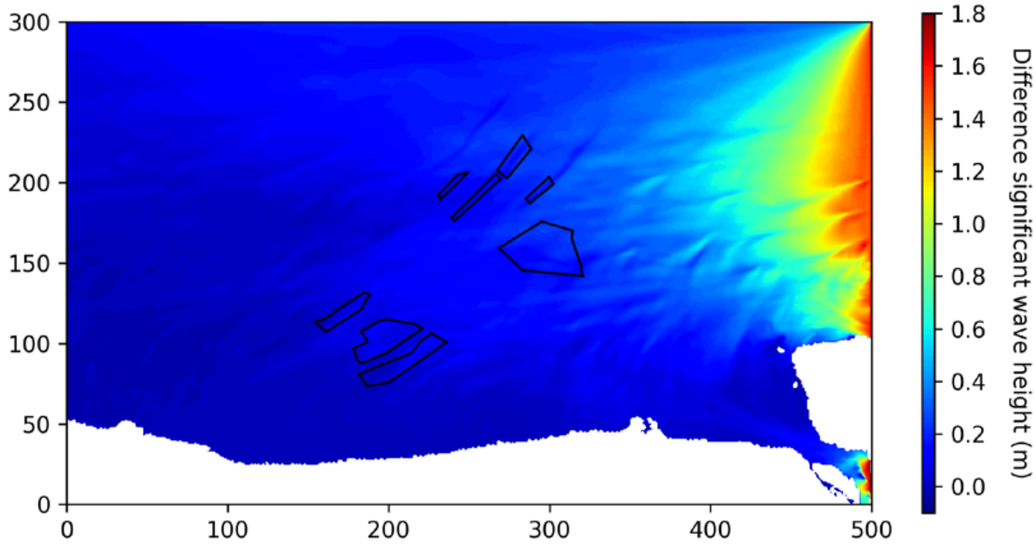

Figure 19: Difference in significant wave height between simulation with boundaries at N, E and W and simulation with boundaries at N. Waves at boundaries: Hs=2.0m, Tp=7s, Dir=NE; wind speed Ws=14 m/s.

In Figure 22, the difference in significant wave height is shown between the two simulations for the three wave and wind directions for the coastal stations defined above and for Westhinder. The maximum differences occur for the waves coming from SW. In stations Nieuwpoort and Oostende an increase of 0.07 m is found when applying boundary conditions at the N, E and W boundary compared to applying only boundaries at the N boundary. Since Westhinder is closer to the western boundary, the increase in significant wave height is considerable in this case, i.e. 0.62 m (from 2.49 m for boundaries at N, E and W boundary to 1.87 m for boundaries at N only). For the simulation with winds coming from NE, a small increase in significant wave height is found at the stations at the eastern coast, up to 0.07 m at station Zeebrugge. For winds coming from the NNW, the difference in significant wave height at the Belgian coast remains limited to less -0.02 m (decrease at Oostende).

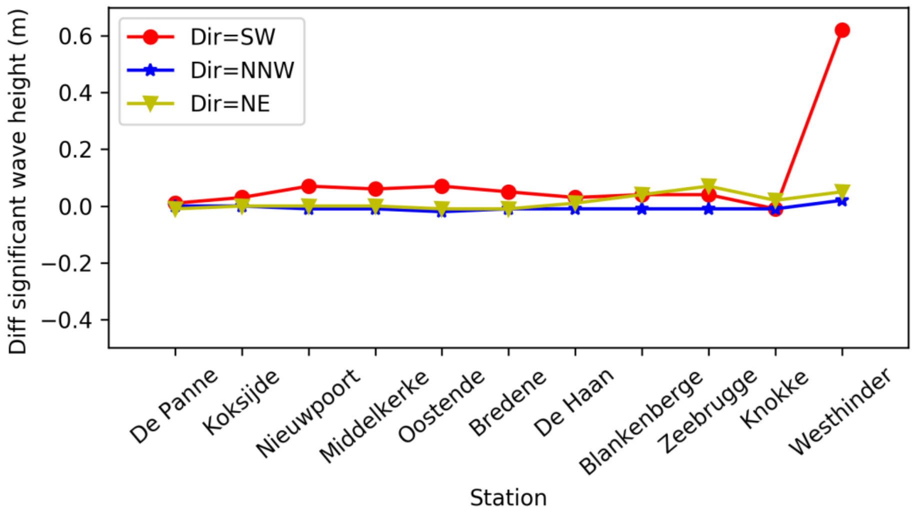

Figure 20: Difference in significant wave height between simulation with boundaries at N, E and W and simulation with boundaries at N. Waves at boundaries: Hs=2.0m, Tp=6s, Dir=NE; wind speed Ws=14 m/s.

The differences in mean period are presented in Figure 21. The largest difference is again for winds coming from the SW, with an increase of 0.31 s for station Nieuwpoort (and 0.89 s for Westhinder). The increase for winds coming from NE and N remains limited to 0.15 s at Blankenberge and Zeebrugge and to 0.05 s at De Panne and Middelkerke respectively.

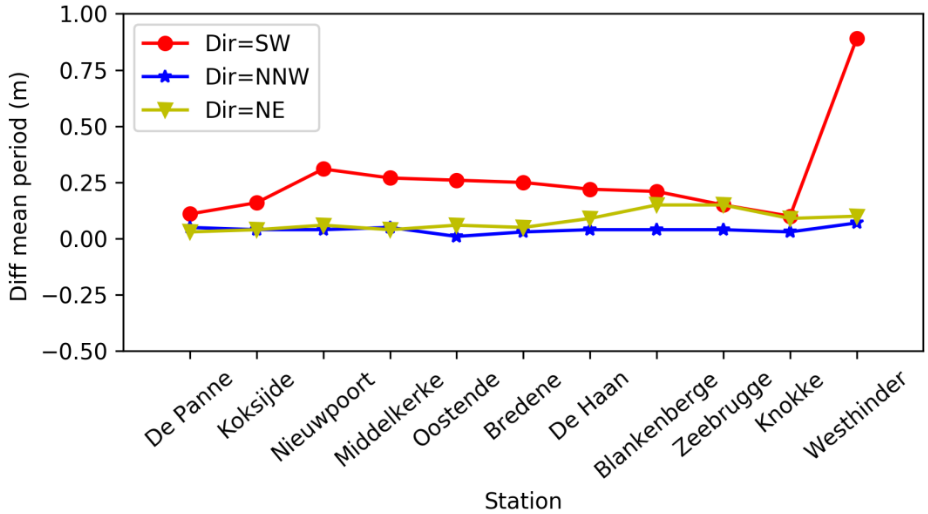

Figure 21: Difference in mean period between simulation with boundaries at N, E and W and simulation with boundaries at N. Waves at boundaries: Hs=2.0m, Tp=6s, Dir=NE; wind speed Ws=14 m/s.

It is important to realise that these differences as such are not important. In the report the effect of the extraction of sand on the propagation of waves to the Belgian coast is investigated. However, these simulations give an indication on the differences one can expect from changing the boundary conditions. In the rest of the report the waves will be applied at the three boundaries, i.e., N, E and W, since these seem to give the most realistic results.

4.3. Simulations for normal climate

For the effect of the extraction of sand at the propagation of the waves to the Belgian coast, a total of 108 simulations have been executed. Three different wave heights were applied at the boundaries of the model, i.e., Hs = 2 m, 3 m and 4 m. In Verwaest et al. (2008), a wave climate for the Belgian coast, based on measurements at station Westhinder was derived. They estimated that around 9.4 % of the time, wave heights of 2 m or higher were encountered at Westhinder with wind/wave direction between SW, N and NE. Waves with significant wave height of 3 m and 4 m are already more extreme cases.

Furthermore, in Verwaest et al. (2008) a relation was proposed between the wave height and the peak period and between the wave height and the wind speed for the waves with significant wave height of 2 m, which are peak period Tp= 7 s and wind speed Ws = 14 m/s. Based on these relationships, values were proposed for significant wave heights of 3 m and 4 m as well, see Table 4. Simulations were performed for 9 different wave and wind directions, going from SW to NE, with a resolution of 22.5°. Furthermore, simulations were executed for low waters and high waters. Low water was set at 0 m TAW, i.e. at -2.33 m below MSL, while high water was set at +2.33 m MSL. To test the effect of the extraction of sand, simulations were of course executed for the reference bathymetry and for the bathymetry with the new proposed extraction limit level. As such, a total of 108 simulations have been executed.

Table 4: Significant wave height, peak period and wind speed for the simulations

Significant wave height (m)	Peak period (s)	Wind speed (m/s)
2	7	14
3	8	18
4	9	22

Some results are first presented for the coastal stations (and Westhinder) in a first section, since this is the main objective of this report. Some more general results are presented in a second section.

4.3.1. Results at the coastal stations

In Figure 22 to Figure 27 for the different coastal stations (and for station Westhinder) and for the different wave and wind directions, the difference in significant wave height is given for the different significant wave heights at the boundaries (and the corresponding wind speed) and for the HW and LW water levels. As a reference in Figure 28, also the significant wave heights are given for boundary conditions with significant wave height of 4 m and for the wind and wave directions of SW, NNW and NE.

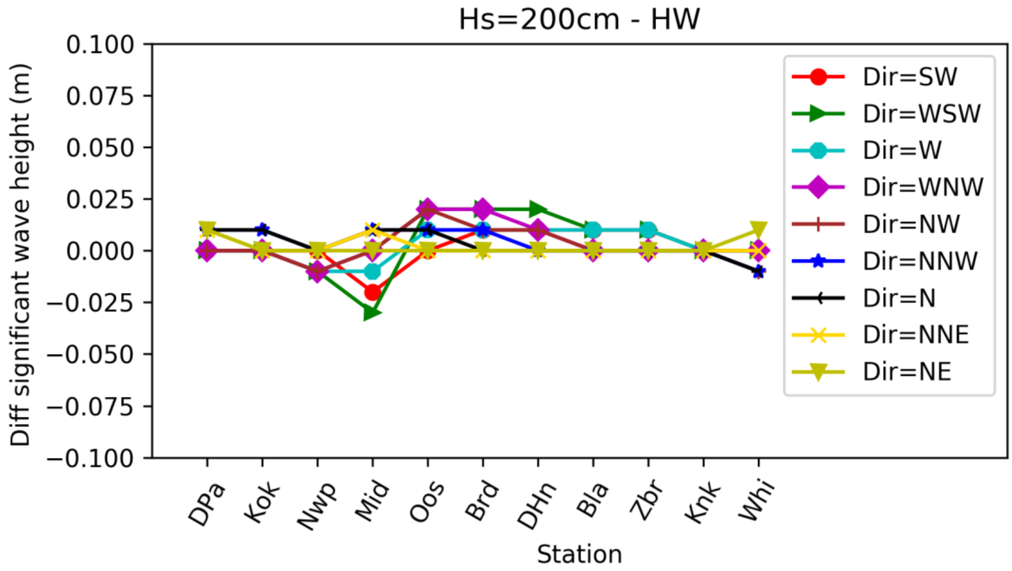

Figure 22: Increase of significant wave height at coastal stations and Westhinder for simulation with the new proposed extraction limit compared to without extraction. Waves at boundary with significant wave height of 2.0 m, wind speed = 14 m/s, different wave and wind directions. HW situation (MSL +2.33 m).

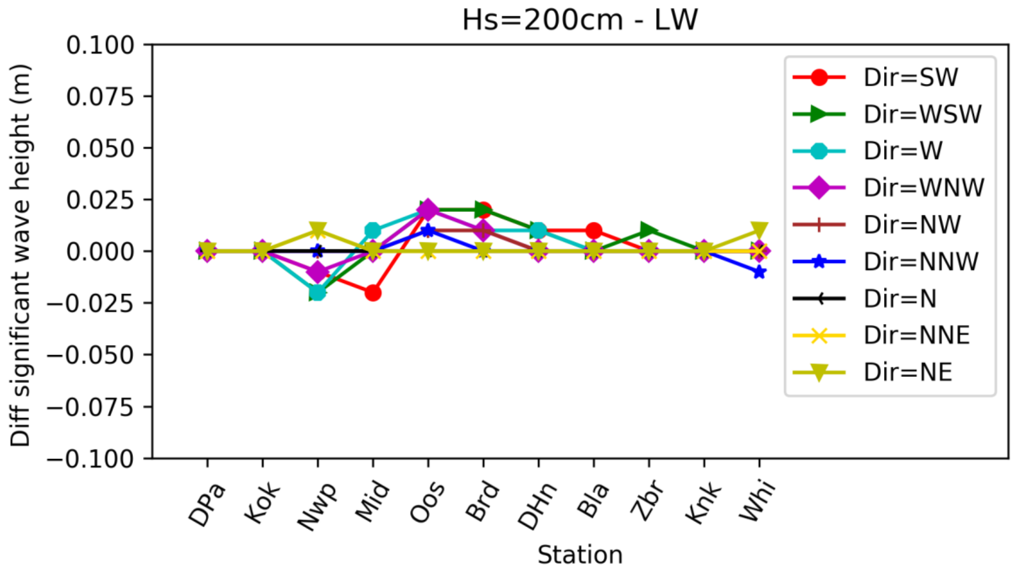

Figure 23: Increase of significant wave height at coastal stations and Westhinder for simulation with the new proposed extraction limit compared to without extraction. Waves at boundary with significant wave height of 2.0 m, wind speed = 14 m/s, different wave and wind directions. LW situation (MSL -2.33 m).

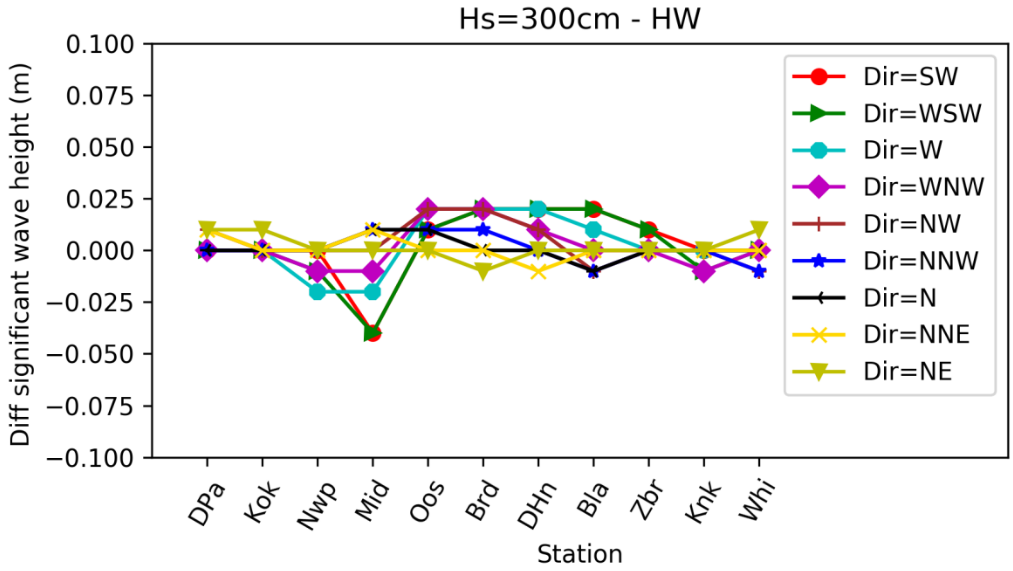

Figure 24: Increase of significant wave height at coastal stations and Westhinder for simulation with the new proposed extraction limit compared to without extraction. Waves at boundary with significant wave height of 3.0 m, wind speed = 18 m/s, different wave and wind directions. HW situation (MSL +2.33 m).

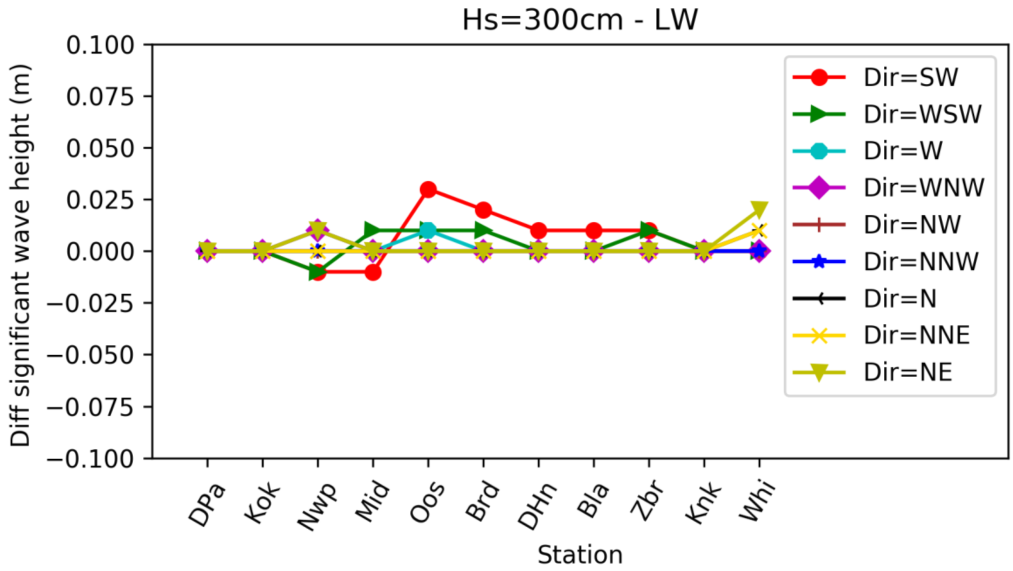

Figure 25: Increase of significant wave height at coastal stations and Westhinder for simulation with the new proposed extraction limit compared to without extraction. Waves at boundary with significant wave height of 3.0 m, wind speed = 18 m/s, different wave and wind directions. LW situation (MSL -2.33 m).

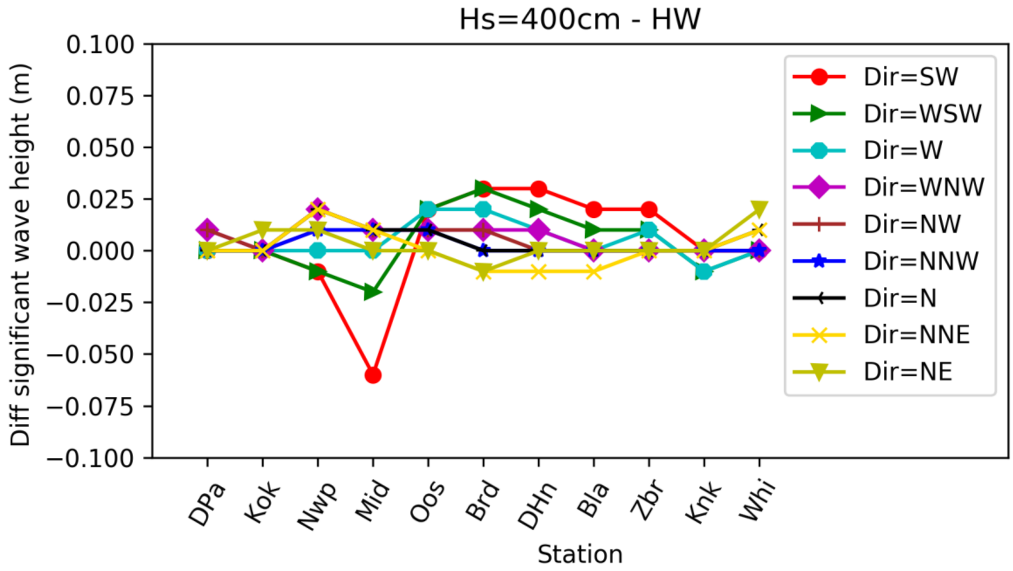

Figure 26: Increase of significant wave height at coastal stations and Westhinder for simulation with the new proposed extraction limit compared to without extraction. Waves at boundary with significant wave height of 4.0 m, wind speed = 22 m/s, different wave and wind directions. HW situation (MSL +2.33 m).

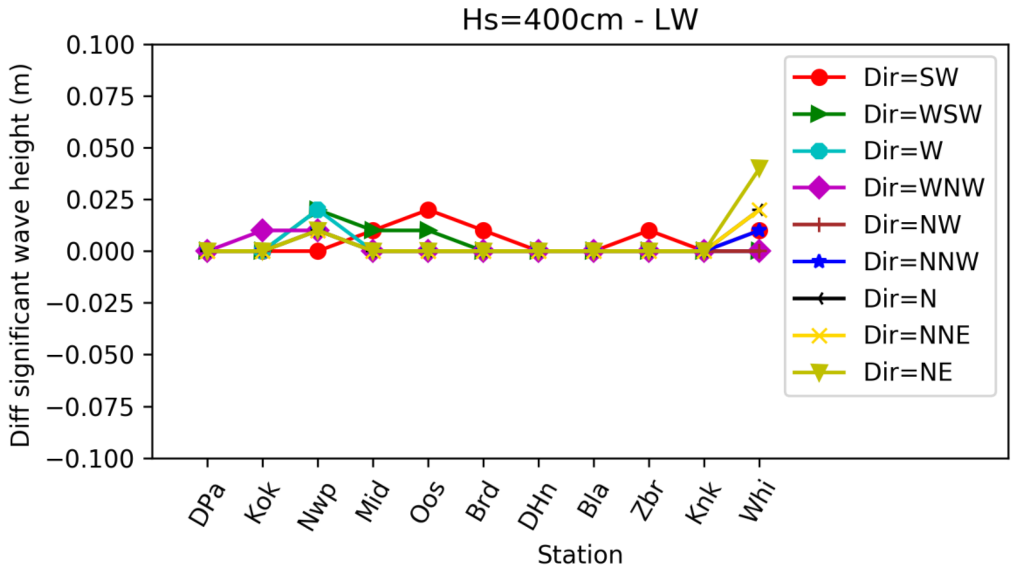

Figure 27: Increase of significant wave height at coastal stations and Westhinder for simulation with the new proposed extraction limit compared to without extraction. Waves at boundary with significant wave height of 4.0 m, wind speed = 22 m/s, different wave and wind directions. LW situation (MSL -2.33 m).

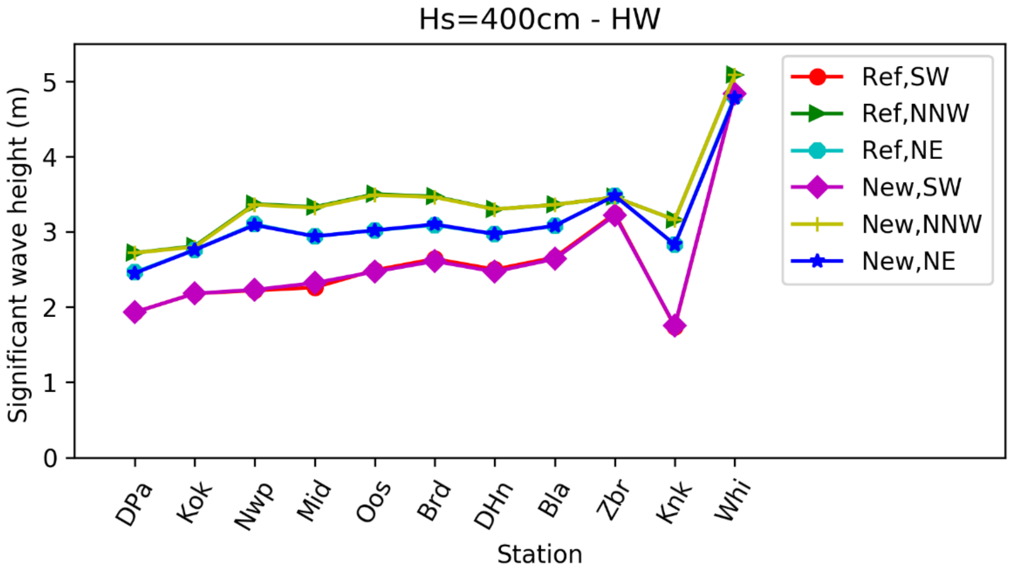

Figure 28: Significant wave height at coastal stations and Westhinder for simulation with the new proposed extraction limit (NEW) compared to without extraction (REF). Waves at boundary with significant wave height of 4.0 m, wind speed = 22 m/s, different wave and wind directions. HW situation (MSL +2.33 m).

For the significant wave height of 2 m at the boundaries, the difference at the coastal stations is limited to 0.02 m or less, both for the HW and the LW water levels, except for station Middelkerke, where a decrease in wave height is expected for HW water level and for waves from WSW of -0.03 m. The effects at the coast are therefore limited. Overall, a small decrease in significant wave height could be expected for some western stations (Nieuwpoort, Middelkerke), while a small increase is expected for some central stations (Oostende, Bredene, De Haan). The effects are slightly larger for the HW water level than for the LW water level.

Similar results are found for a significant wave height of 3 m at the boundaries. At stations Middelkerke, a decrease is found of significant wave height of -0.04 m for winds coming from WSW and SW and for HW. On the other hand, an increase of +0.03 m is found for station Oostende for wind from SW. Also here, for the rest, the differences remain limited to 0.02 m.

For significant wave heights of 4 m at the boundaries and wind speeds of 22 m/s, the changes remain limited. The decrease at station Middelkerke for HW and winds from SW is -0.06 m now, while for the same wind direction, the increase in significant wave height at stations Bredene and De Haan is +0.03 m now. For the rest the results are limited to 0.02 m. To illustrate the limited influence of the sand extraction, the significant wave height for the two simulations is shown for the coastal stations in Figure 28. Although there are differences for the difference coastal stations and for the wind direction, the influence of the sand extraction is limited.

Remark that also at station Westhinder, the changes remain very limited. Only for winds from NE and wave height of 4 m at the boundaries, an increase in wave height is found of +0.04 m.

One can conclude that the highest effects are to be expected at HW water levels, and that in the area Nieuwpoort-Middelkerke a small decrease is expected and in the area Oostende-Bredene-De Haan a small increase is expected. This is illustrated in Figure 29. Furthermore, the highest changes are expected for the largest waves and for the winds from SW and WSW. Overall, however, the effects remain very limited.

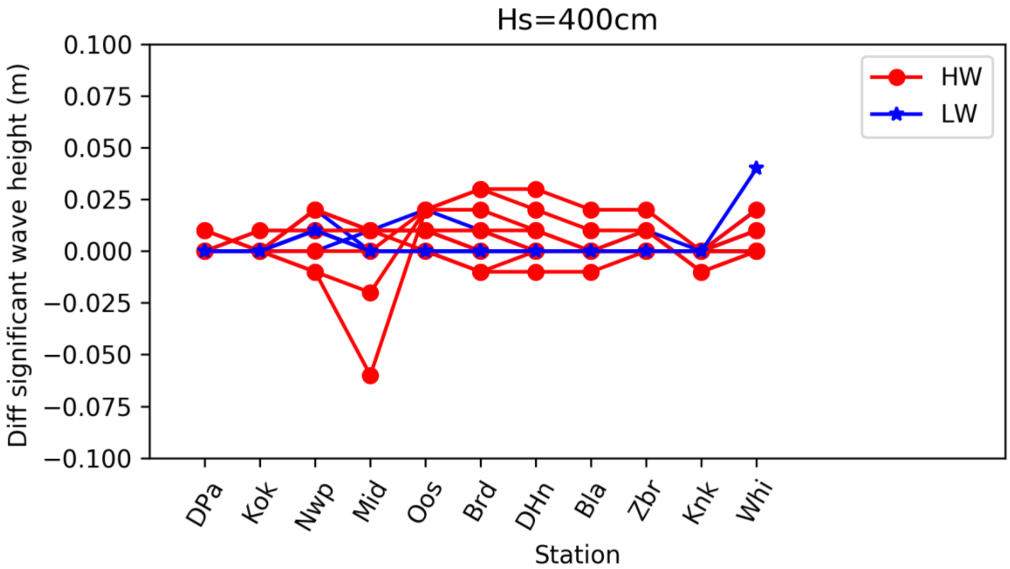

Figure 29: Difference in significant wave height at coastal stations and Westhinder for simulation without extraction and with the new proposed extraction limit. Waves at boundary with significant wave height of 4.0 m, wind speed = 22 m/s.

The changes to the mean period near the coast remain limited to less than -0.09 s or +0.07 s, and are the largest for winds coming from SW. Also the changes in wave direction remain limited to less than +1.7 degrees or -1.4 degrees.

4.3.2. Overall results

In the previous section, it was shown that the results of the new limit for sand extraction has limited effects on the significant wave height at the coastal stations. However, the effect on the Belgian continental shelf itself, more offshore, closer to the extraction zones itself, can be much larger. Some information on this is presented in this section.

In Figure 30 the maximum and the minimum differences are shown in the model grid for the different simulations. One can see that the maximum decrease in wave heights is limited to -0.43 m. The maximum decrease is larger for the waves coming from N to NE. For the maximum increase in wave height, more differences can be observed. First of all, it is clear that for the difference are larger for higher significant wave heights at the boundaries. However, also the water level is of great importance.

The maximum increase for low water (MSL -2.33 m) and for wave heights of 3 m at the boundaries is much larger than the maximum increase for high water (MSL +2.33 m) and for wave heights of 4 m at the boundaries. The maximum differences are for waves coming from NNW (perpendicular to the coast) to NE. The maximum increase during HW is +1.0 m for waves coming from NE, while the maximum increase during LW is +1.85 m for winds coming from N.

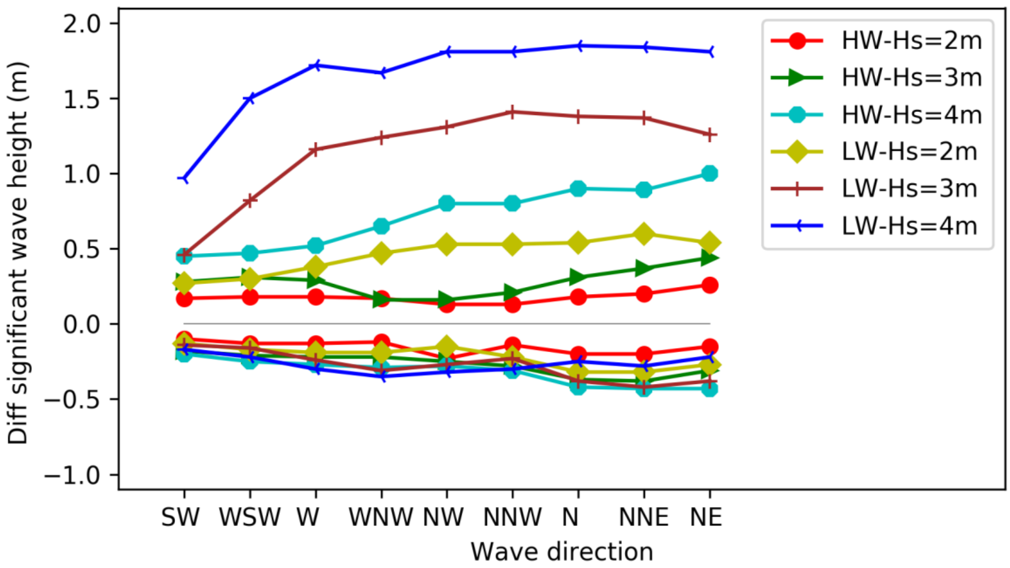

Figure 30: Maximum and minimum difference in significant wave height at the model grid for simulation without extraction and with the new proposed extraction limit as a function of the wind direction, for three different wave heights at the boundaries (*Hs*=2 m – *Ws*=14 m/s; *Hs*=3 m – *Ws*=18 m/s; *Hs*=4 m – *Ws*=22 m/s) and for HW and LW water levels.

In Figure 31, the position of the points where the maximum and the minimum differences in significant wave height are found for all simulations. The maximum differences are mostly found southwest (or south) of the extraction zones 3, mostly around the extraction zone Oostdyck. The minimum differences are found near south of east of the extraction zones 1, 4 and 5, while also two points are found near the coast.

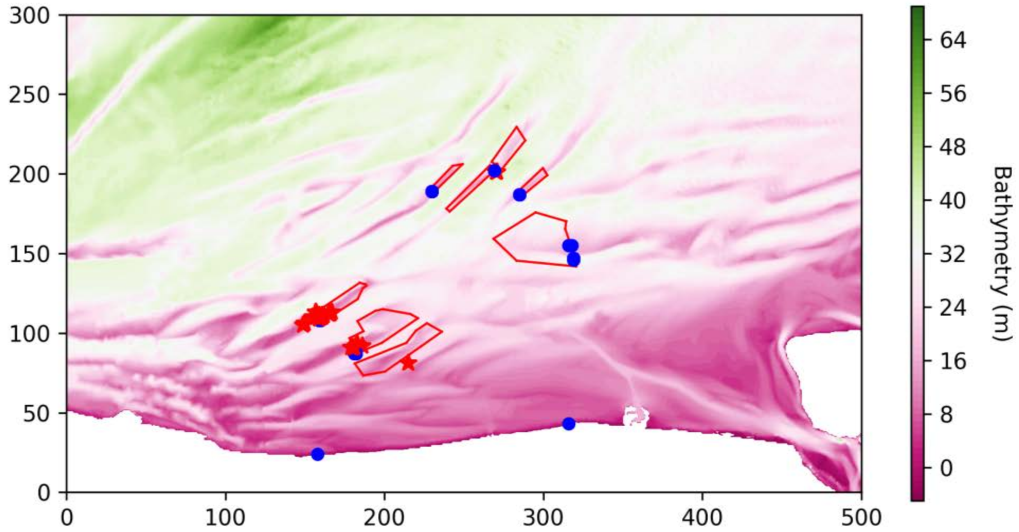

Figure 31: Position of the points were highest increase (red stars) and highest decrease (blue dots) in significant wave height are found for all simulations.

As an example, the significant wave heights for the LW water level, and for significant wave height of 4 m coming from the N, for the simulations with original bathymetry and with the bathymetry, for the new extraction limit are given in Figure 32 and Figure 33. The differences between the two significant wave heights is given in Figure 34.

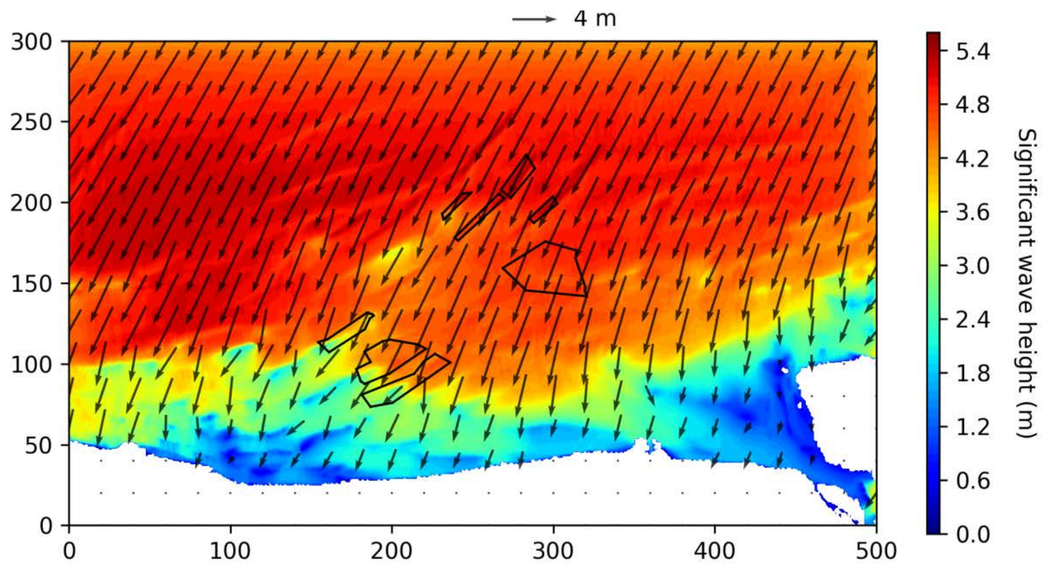

Figure 32: Significant wave height with original bathymetry. Waves at boundaries: Hs=4.0m, Dir=N; wind speed Ws=22 m/s.

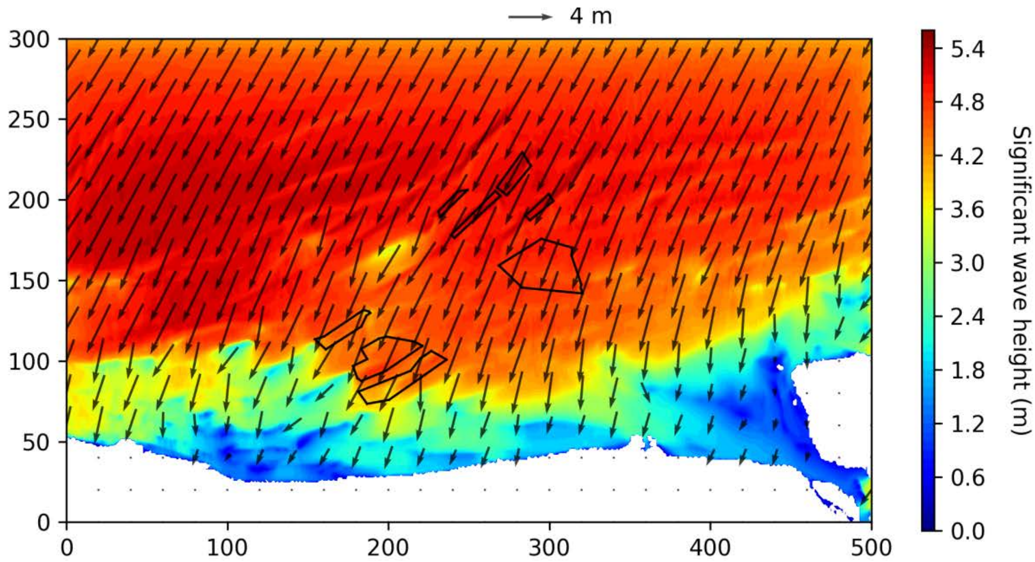

Figure 33: Significant wave height with extraction limit bathymetry. Waves at boundaries: Hs=4.0m, Dir=N; wind speed Ws=22 m/s.

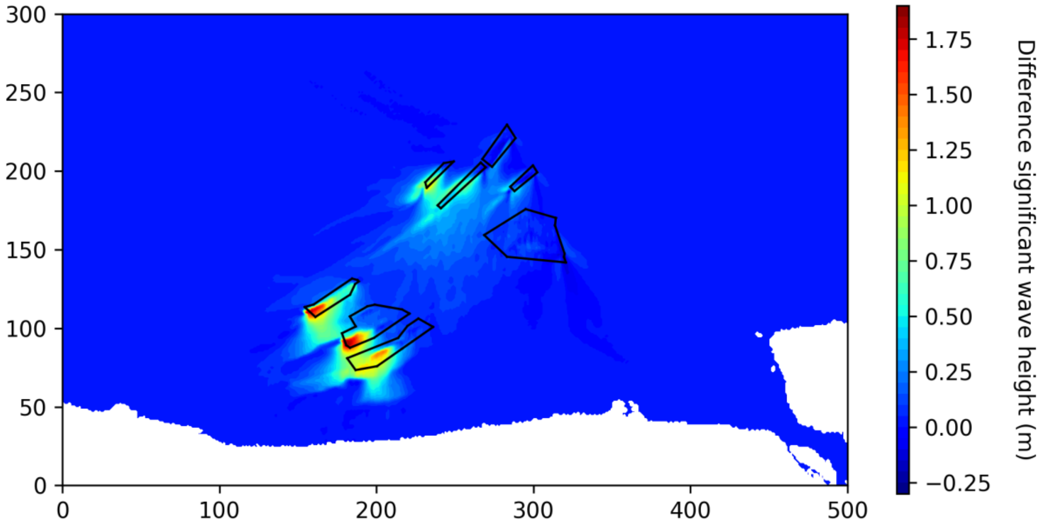

Figure 34: Difference in significant wave height between simulation with extraction limit bathymetry and simulation with original bathymetry. Waves at boundaries: Hs=4.0m, Dir=N; wind speed Ws=22 m/s.

One can see that the effect in the neighbourhood of the extraction zones can be quite considerable, with an increase in significant wave height south of the extraction zone 3 at the Buitenratel of +1.85 m, but that the effect at the Belgian coast is negligible.

4.4. Simulations for 1000 yearly storm

4.4.1. Introduction

Finally, also some simulations were executed for the so-called 1000 yearly storm. In this case waves of 6 m are applied at the boundaries, the water level is set at 7 m above TAW (i.e., at 4.67 m above MSL). The peak frequency is set at 10.5 s and the wind velocity is put at 30 m/s. These parameters are based on de Roo et al. (2014). Normally these boundary conditions are taken at station Westhinder. In this case the same boundary conditions were taken at the boundary of the new grid, which is extended more to the North. The simulations were done for 4 wind directions, which are N, NNW, NW and WNW since these directions contribute to the resulting extreme wave height near the coast and depending on the location, one direction can have more impact due to sand mining than the other.

To take into account possible sea level rise on a longer term, reference was taken to the recent report of CREST and Coastal Project Coastal Vision (2019), were common climate change scenarios for the Belgian coast were proposed. For the current study, the values for the IPCC (2013) RCP4.5 and RCP8.5 were taken, using a sea level rise of +0.60 m and +0.85 m respectively for the year 2100.

Although it is very unlikely that a 1000 yearly storm with waves with significant wave height up to 6 m at the boundary occur with no storm surge, the simulations were also done with low water situation, thus with water level at MSL -2.33 m as reference.

The simulations were executed for the reference bathymetry and for the bathymetry with the new proposed extraction limit for extraction.

4.4.2. Results at the coastal stations

As for the normal climate, the results at the coastal stations are presented first. In Figure 35, the significant wave heights at the coastal stations and at Westhinder are shown for the 1000 yearly storm with boundaries of significant wave height of 6 m and wind speed of 30 m/s. One can see that the significant wave height at De Panne and Koksijde remains below 4 m, while at the coastal stations from Nieuwpoort to Blankenberge, the significant wave height varies around 4.5 m. At Zeebrugge, the station a little bit more offshore, a significant wave height of more than 5 m is reached. At Westhinder, a significant wave height of more than 7.5 m is reached for winds from the WNW. Overall the highest wave heights are obtained for winds from the NW. Since the wave height is clearly higher than 6 m at Westhinder, the simulations represent an even extremer case than the 1000 yearly storm, with significant wave height of 6 m at Westhinder.

In Figure 36 to Figure 39, the differences in significant wave height at the coastal stations (and Westhinder) are shown for the different simulation and for the different water levels, due to the sand extraction.

One can see that the effects at the coastal stations also in these cases remain limited. Most effects are seen for waves and winds coming from NW and especially WNW. Only in these cases changes of more than 0.02 m are expected. The largest increase in significant wave height is for a sea level rise of +0.85 cm, where the increase in significant wave height is +0.05 m at station Nieuwpoort. For the current sea level, at station Zeebrugge and Knokke a decrease of significant wave heights is found of -0.04 m and -0.03 m respectively. Overall the effects are negligible.

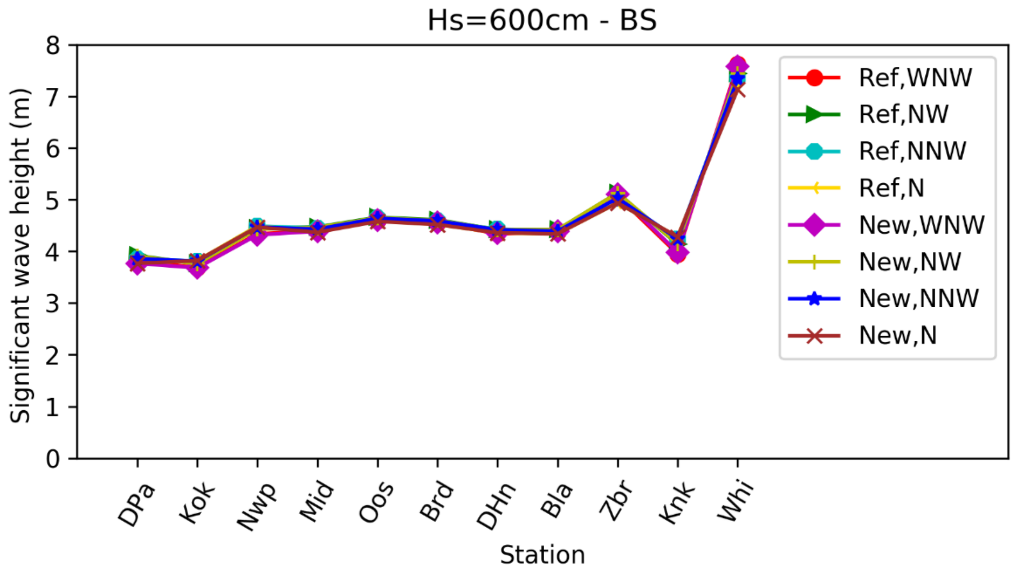

Figure 35: Significant wave height at coastal stations and Westhinder for simulation with the new proposed extraction limit (New) compared to without extraction (Ref). Waves at boundary with significant wave height of 6.0 m, wind speed = 30 m/s, water level at 4.67 m MSL (1000 yearly storm). Results for different wave and wind directions.

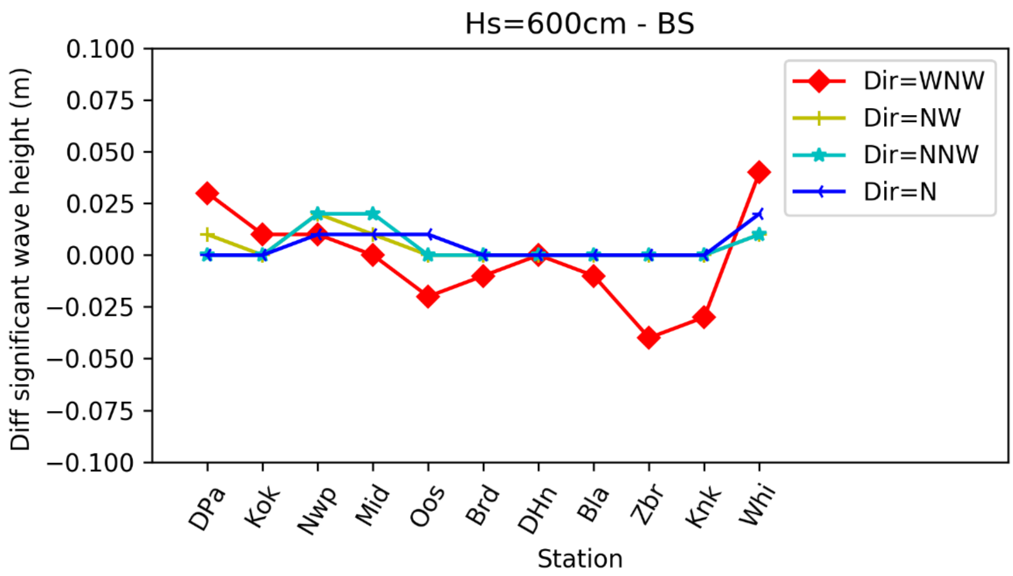

Figure 36: Increase of significant wave height at coastal stations and Westhinder for simulation with the new proposed extraction limit compared to without extraction. Waves at boundary with significant wave height of 6.0 m, wind speed = 30 m/s, water level at 4.67 m MSL (1000 yearly storm). Results for different wave and wind directions.

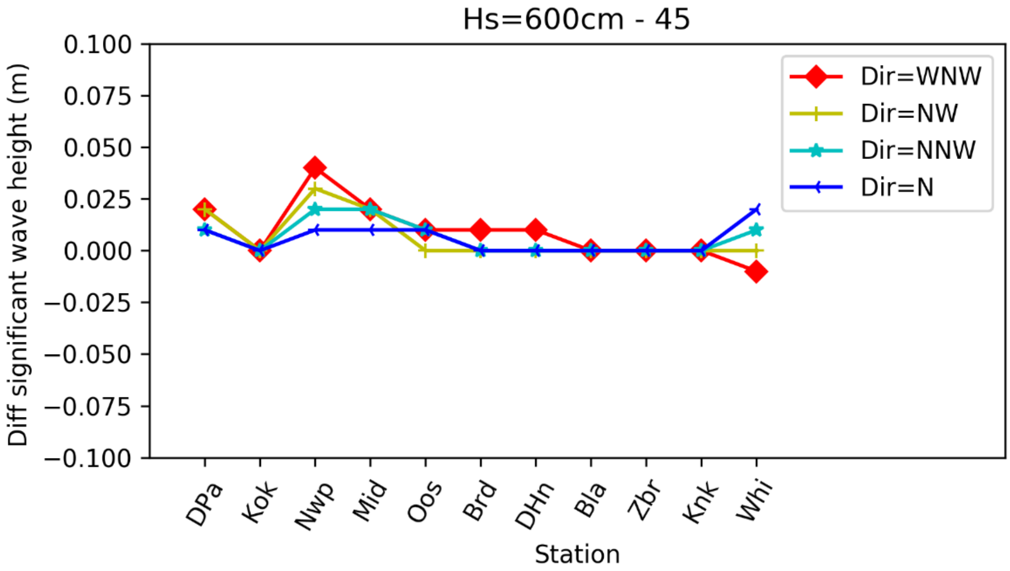

Figure 37: Increase of significant wave height at coastal stations and Westhinder for simulation with the new proposed extraction limit compared to without extraction. Waves at boundary with significant wave height of 6.0 m, wind speed = 30 m/s, water level at 5.27 m MSL (1000 yearly storm + sea level rise RCP 4.5). Results for different wave and wind directions.

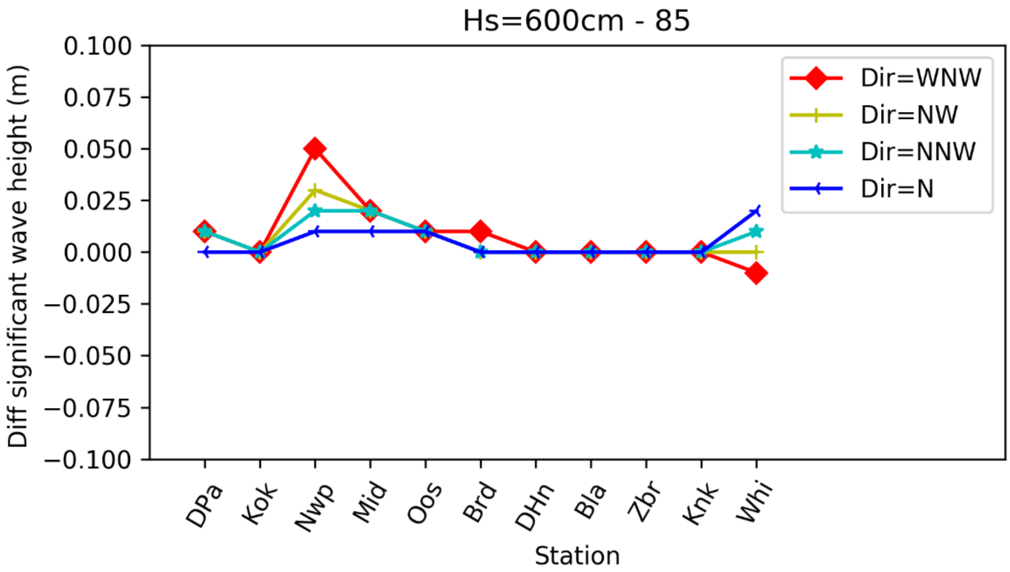

Figure 38: Increase of significant wave height at coastal stations and Westhinder for simulation with the new proposed extraction limit compared to without extraction. Waves at boundary with significant wave height of 6.0 m, wind speed = 30 m/s, water level at 5.52 m MSL (1000 yearly storm + sea level rise RCP 8.5). Results for different wave and wind directions.

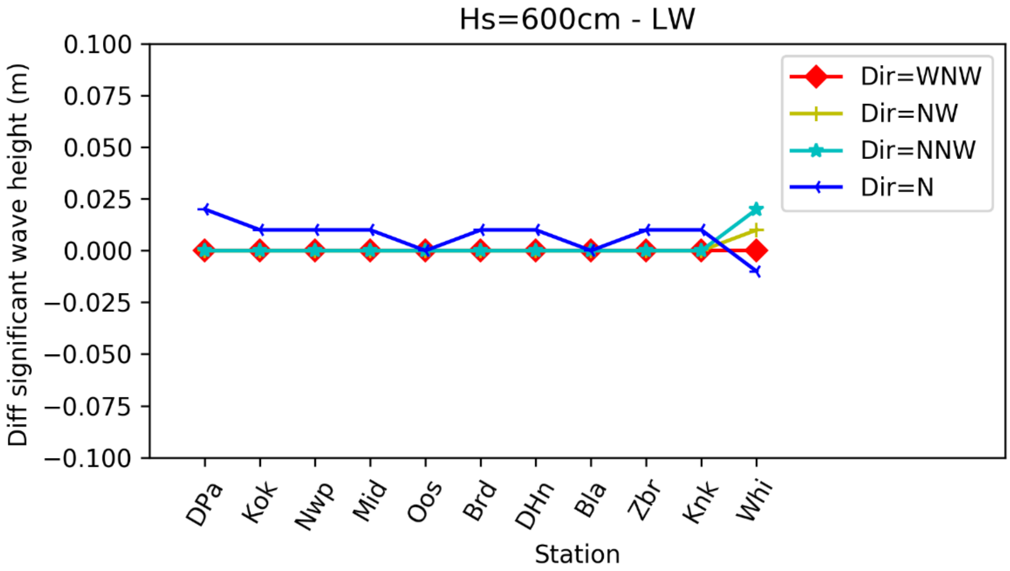

Figure 39: Increase of significant wave height at coastal stations and Westhinder for simulation with the new proposed extraction limit compared to without extraction. Waves at boundary with significant wave height of 6.0 m, wind speed = 30 m/s, water level at -2.33 m MSL (1000 yearly storm – low water). Results for different wave and wind directions.

For the situation with the 1000 yearly storm during low water level, the changes at the coastal stations are even less and are always below 0.02 m. Only for winds from N, an increase in significant wave height of +0.02 m is found for station De Panne. The differences are less than 1% of the obtained wave height in the considered points.

4.4.3. Overall results

The results at the Belgian Continental Shelf, more offshore, near the extraction zones are again much higher, as expected.

In Figure 40, again the maximum and the minimum differences are shown in the model grid for the different simulations. One can see that the maximum decrease in wave heights is again limited to -0.53 m, in this case for RCP 4.5 and for waves from NW. The maximum increase in wave heights for the 1000 yearly storm is +1.52 m for the waves coming from the North. This maximum increase is slightly lower when sea level rises of +0.60 m or +0.85 m are taken into account. For the 1000 yearly storm during low water (MSL -2.33 m) the maximum increase in significant wave height is much higher, up to +2.72 m, in this case from waves coming from the WNW.

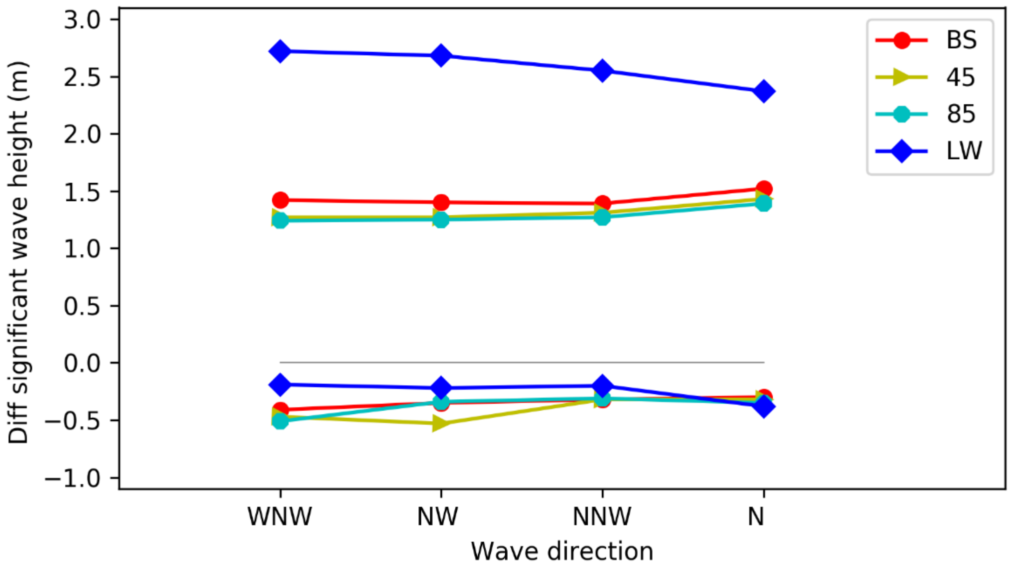

Figure 40: Maximum and minimum difference in significant wave height at the model grid for simulation without extraction and with the new proposed extraction limit as a function of the wind direction, for the 1000 yearly storm (at the boundaries *Hs*=6 m – *Ws*=30 m/s) and for different water levels: BS=+4.67 m MSL, 45=5.27 m MSL, 85=5.52 m MSL, LW=-2.33 m MSL.

The significant wave height for the 1000 yearly storm, for the two bathymetries are shown in Figure 41 and Figure 42. The differences between the two significant wave heights is given in Figure 43.

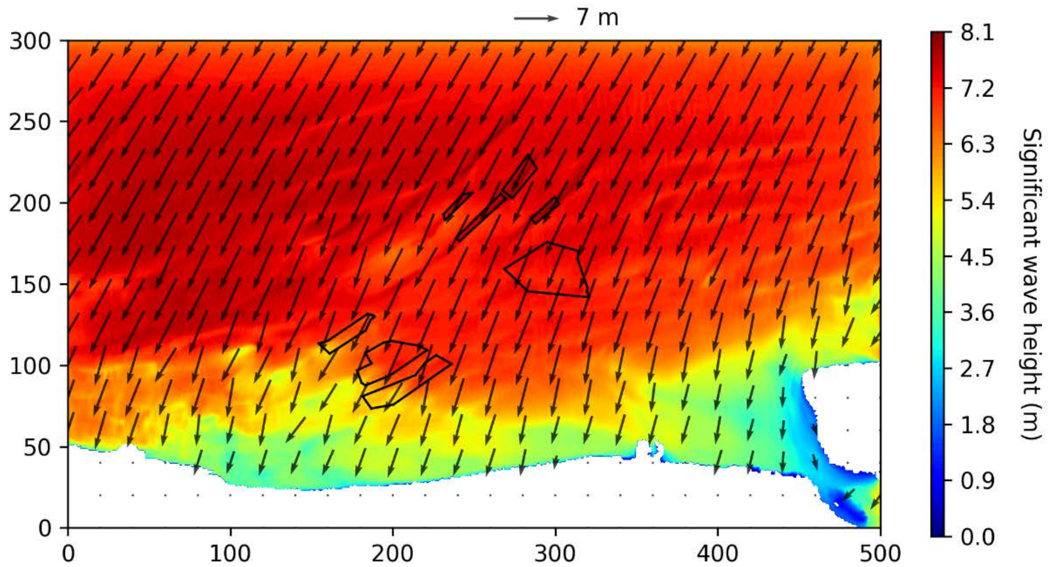

Figure 41: Significant wave height with original bathymetry for 1000 yearly storm. Waves at boundaries: Hs=6.0m, Dir=N; wind speed Ws=30 m/s, water level=4.67 m MSL.

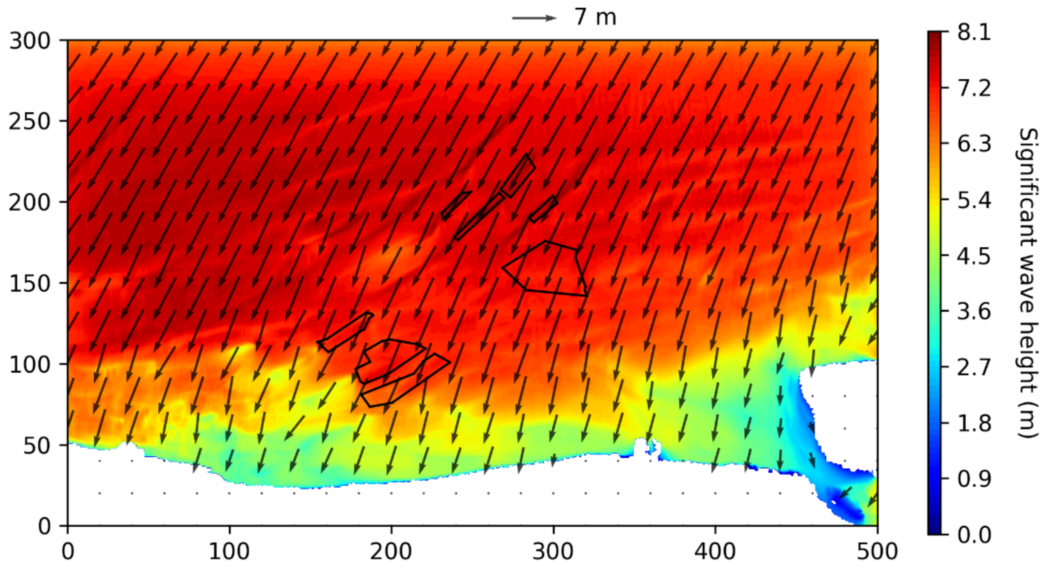

Figure 42: Significant wave height with extraction limit bathymetry for 1000 yearly storm. Waves at boundaries: Hs=6.0m, Dir=N; wind speed Ws=30 m/s, water level=4.67 m MSL.

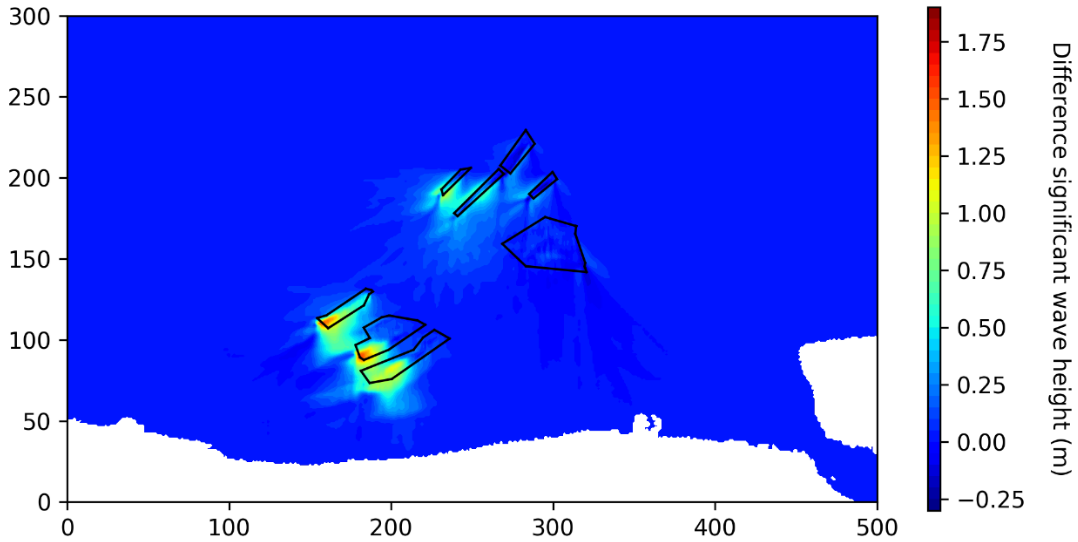

Figure 43: Difference in significant wave height between simulation with extraction limit bathymetry and simulation with original bathymetry for 1000 yearly storm. Waves at boundaries: Hs=6.0m, Dir=N; wind speed Ws=30 m/s, water level=4.67 m MSL.

5. Discussion on the effect of sand extraction on coastal protection

To evaluate the effects on coastal protection one considers the normal wave climate as well as the wave conditions during 1000 yearly storm conditions. The water levels can be assumed to be unaltered by the extraction scenarios due to the small size of the extraction zones compared to the southern North Sea area at which scale tides and storm surges are generated.

The normal wave climate drives changes in the coastline position. Positive gradients in alongshore transport and net cross-shore transport which is off-shore directed induce erosion of the coastline. The intensities of these transports are proportional with the significant wave height. From the SWAN model results, one observes very small changes of the significant wave heights along the coast, less than ±1 % on average. The impact of these changes on coastline erosion can be considered negligible.

The conditions during a 1000 yearly extreme storm determine the coastal safety level. Higher wave heights will result in larger erosion of dunes and dry beaches and in more overtopping of sea dikes and structures in the harbours. From the SWAN model results, one observes a very small increase of the wave height, 0.05 m maximum. However, this increase is so small that it can be considered negligible for the evaluation of the coastal safety level. This is confirmed by results of an earlier evaluation of sand extraction at the Kwintebank from coastal safety perspective (Verwaest and Verelst, 2006).

It can be concluded that the effect on coastal protection of the sand extraction scenarios considered is negligible. This conclusion is attributed to the large distance from the extraction sectors to the coastline, namely more than 10 km.

6. Conclusions

In the present report, the effect of extraction of marine aggregates on wave propagation to the Belgian coast was studied. More especially, the impact of a newly proposed extraction limit levels, as proposed by Degrendele (2016) and Degrendele et al. (2017), on the wave propagation was investigated.

In a first section, a new bathymetry for the SWAN model was constructed, which extended more to the North, to include in the model the different extraction zones. The bathymetries, which were provided by COPCO were inserted in the bathymetry, to simulate the propagation of the waves to the Belgian coast for the two bathymetries and to estimate the increase or decrease of the significant wave height at the coast. Ten coastal stations were defined for the coastal municipalities to compare the results.

First, the effect of the boundaries was tested. It was concluded that using bathymetries at the northern boundary only or using boundaries at the northern, eastern and western boundaries didn't influence the result at the Belgian coast significantly.

For the current climate 108 different simulations were executed with different significant wave heights at the boundaries (2 m, 3 m and 4 m), for different water levels (high water and low water) and for different wind and wave directions from SW to NE with an increment of 22.5°. The results showed that the effect of the extraction on the significant wave height at the coastal stations is very limited. Although in the neighbourhood of the extraction zones, an increase of significant wave height is possible up to +1.85 m, the effect at the coastline is negligible. Therefore, it can be concluded that the impact of the extraction scenarios on coastline erosion can be considered negligible.

For 1000 yearly storm conditions, some simulations were executed, including the effect of possible sea level rise (up to +0.85 m) until 2100. It was clear that large effects on the wave heights can be expected near the extraction zones, especially during low water situations, but that the effect at the coastline remains very limited to an increase of +0.05 m maximum (less than 1% increase). It can be concluded that the impact of the extraction scenarios on the coastal safety level is negligible.

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